Liquid Scintillator detectors

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The INFN School on Underground Physics

SOUP2024 3rd School On Underground Physics - Bertinoro 14-18 October 2024

Outline

Organic Liquid Scintillators

- What are liquid scintillators?

Use of Organic Liquid Scintillators in Underground physics

- Requirements for their use in large rare event detectors
- Past and present experiments based on LS
- Energy, position and direction reconstruction

The future of organic Liquid Scintillators

- Hybrid Liquid scintilators
- Liquid0

What are liquid scintillators?

DISCLAIMER

- Scintillators are used in many fields (nuclear, medical..): in this lesson, I will specifically concentrate on their use in underground physics (which is the main focus of SOUP);
- I will talk only about **organic** liquid scintillators (liquid scintillators based on noble elements (Argon, Xenon) have already been covered in two lessons on Tuesday);
- I have not time to describe ALL expriments which use organic liquid scintillators. I will mention only some of them, highlighting the common aspects and specific features;
- All the experiments I am going to discuss use **photomultiplier tubes** to detect photons emitted by liquid scintillators: I won't go in any details concerning how phototubes work, since there will be a dedicated lesson on photon detectors on Friday;

Requirements for underground experiments

RARE EVENTS →

- Large Masses
- Long data-taking (stability in time)

Background Control →

- Underground facilities
- Shielding Strategy
- Veto system
- Radiopurity

Info for each event →

- Count signal events
- Measure energy
- Measure position of interaction
- Measure direction

Organic liquid scintillators?

RARE EVENTS →

- Large Masses OK!
- Long data-taking (stability in time) OK?

Background Control →

- Underground facilities
- Shielding Strategy
- Veto system
- Radiopurity OK!

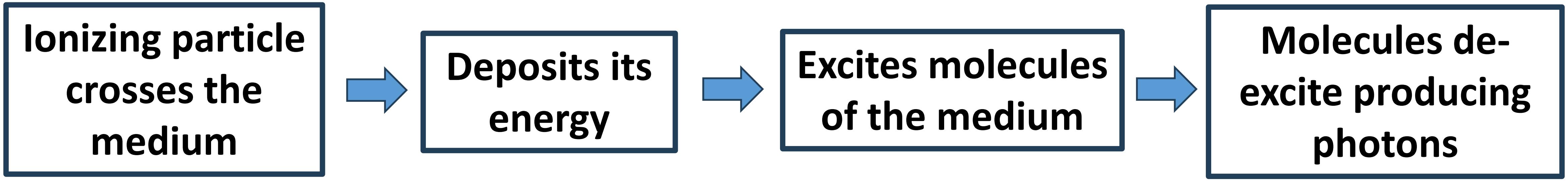
Info for each event →

- Count signal events OK!
- Measure energy OK!
- Measure position of interaction OK!
- Measure direction NO or..?

What are organic liquid scintillators?

Organic compounds: the π-bond

- Based on organic substance (C, H) mostly derivated from petroil;

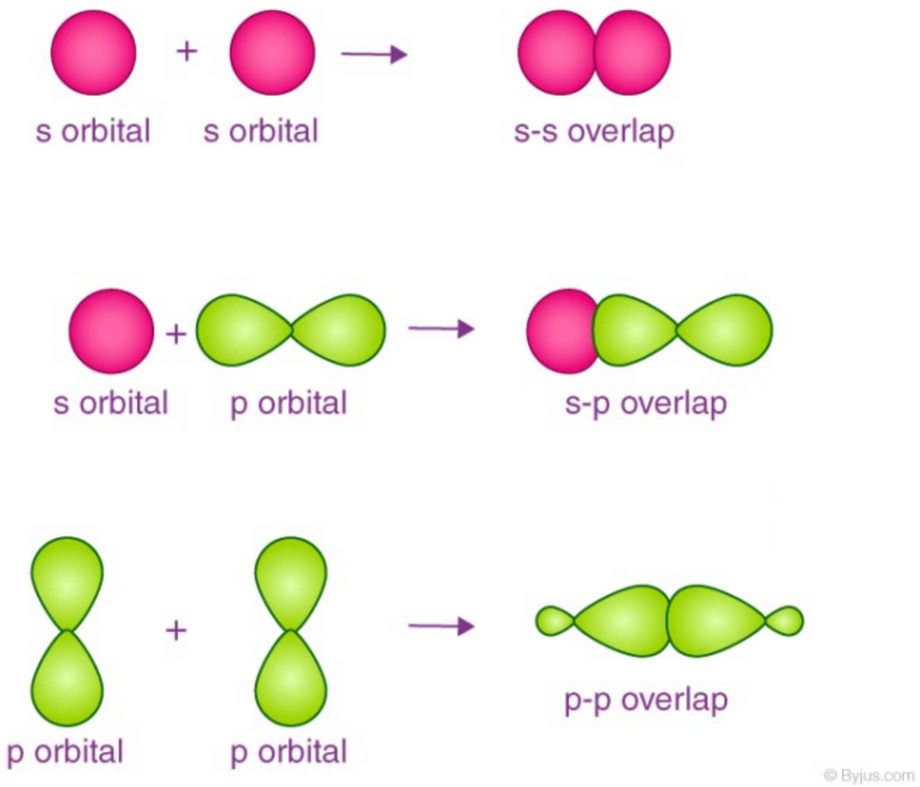


Ionizing particle crosses the medium → **Deposits its energy** → **Excites molecules of the medium** → **Molecules de-excite producing photons**

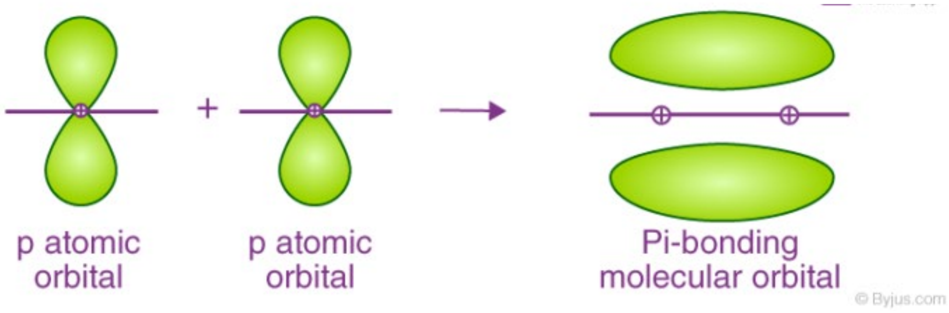
- This process is independent from the physical state (gaseous, solid or liquid) of the substance;
- The light emission properties are strictly connected to the bonding characteristics of the CARBON atoms which make up an organic material, in particular the covalent **π-bond**

Organic compounds: the π-bond

σ-bond: superposition of s-s, s-p, or p-p or hybrid orbitals head to head
The distribution of electrons concentrated on the bonding axis



π-bond: superposition of p-p orbitals side by side
The distribution of electrons is concentrated symmetrically in two regions on opposite side of the bonding axis



- The π–bond is weaker than the σ-bond
- Fluorescence is due to the transition between excited states of electrons in the π–bond

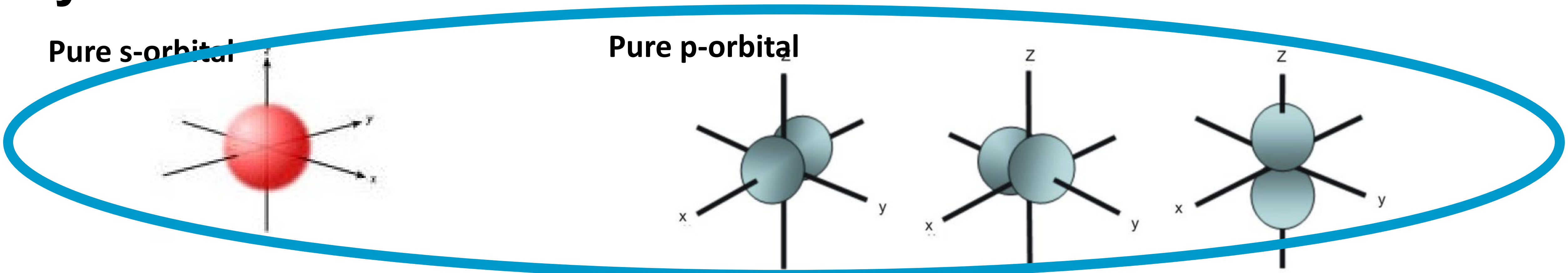
Organic compounds: the π-bond

Hybridization in Carbon atoms

- Carbon structure is $1s^2$ **$2s^2$ $2p^2$**
- The 4 valence electrons can be found in the excited configuration $1s^2$ **$2s^1$ $2p^3$**
- When atoms bond to form molecules, a mixing between the pure s and p orbital (hybridization) can occur;
- The hybridization type influences the shape of the final molecule and also the strenght of the bonding;

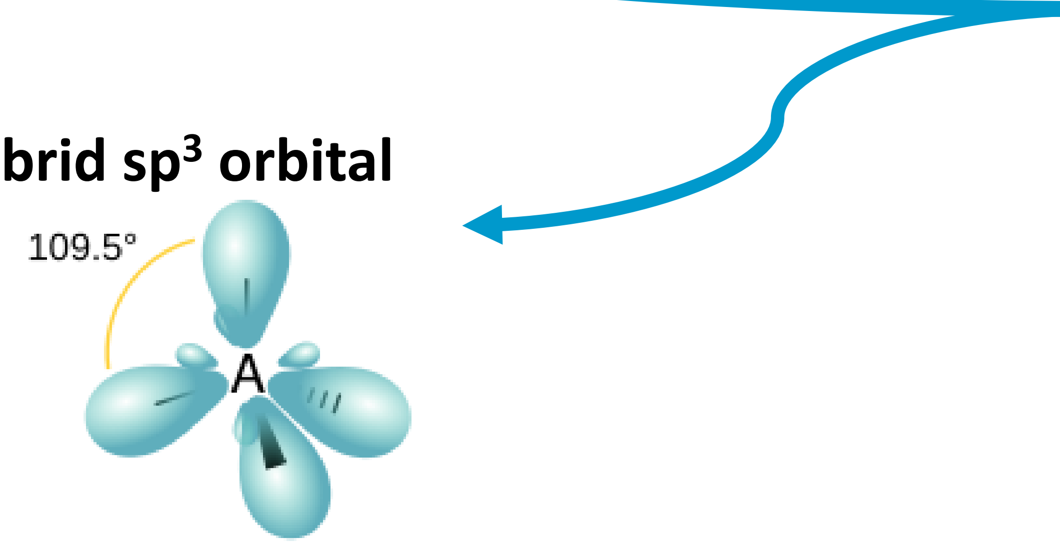
Organic compounds: the π-bond

Hybridization



Pure s-orbital

Pure p-orbital



Hybrid sp³ orbital

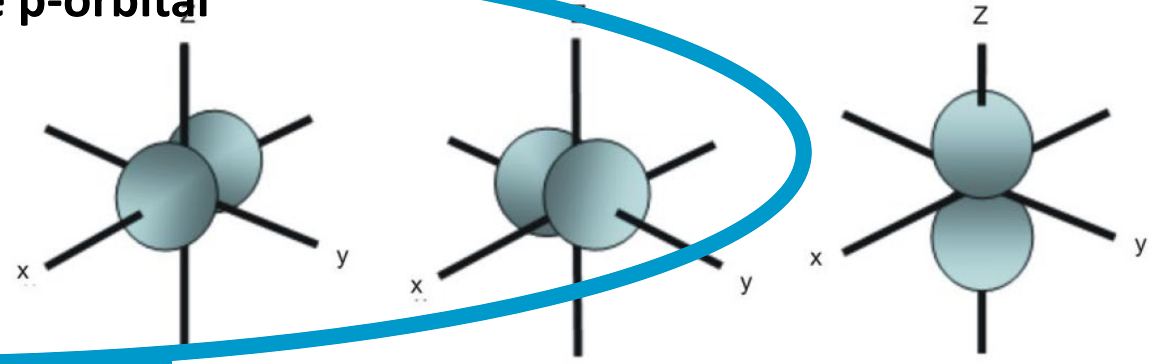
- 4 hybrid orbitals
- 4 σ-bonds
- Tetrahedron
- Example: methane, diamond
- **No fluorescence**

Organic compounds: the π-bond

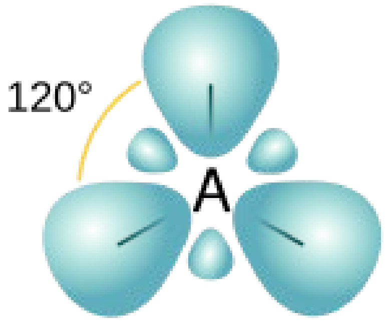
Hybridization

Pure s-orbital

Pure p-orbital



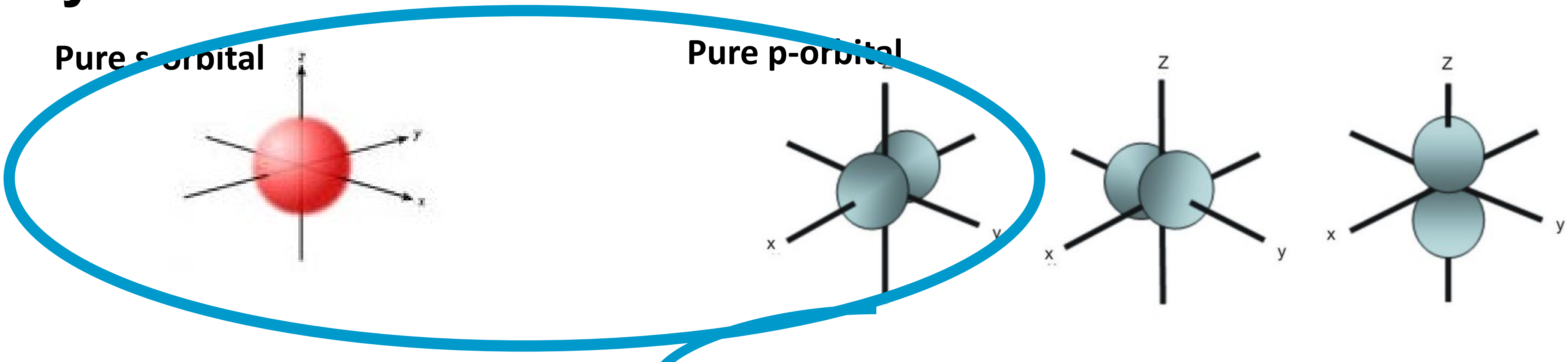
Hybrid sp^2 orbital

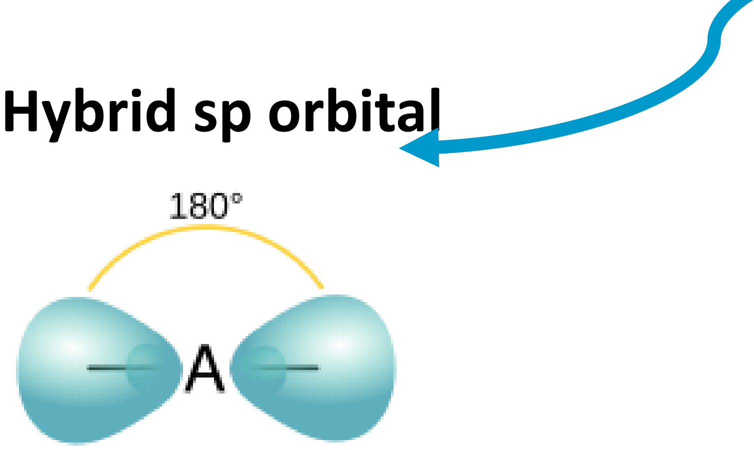


- 3 hybrid orbitals + 1 p orbital
- 3 σ-bonds + 1 π-bond
- Planar
- Example: benzene and polycyclic aromatic hydrocarbons
- **Fluorescence**

Organic compounds: the π-bond

Hybridization

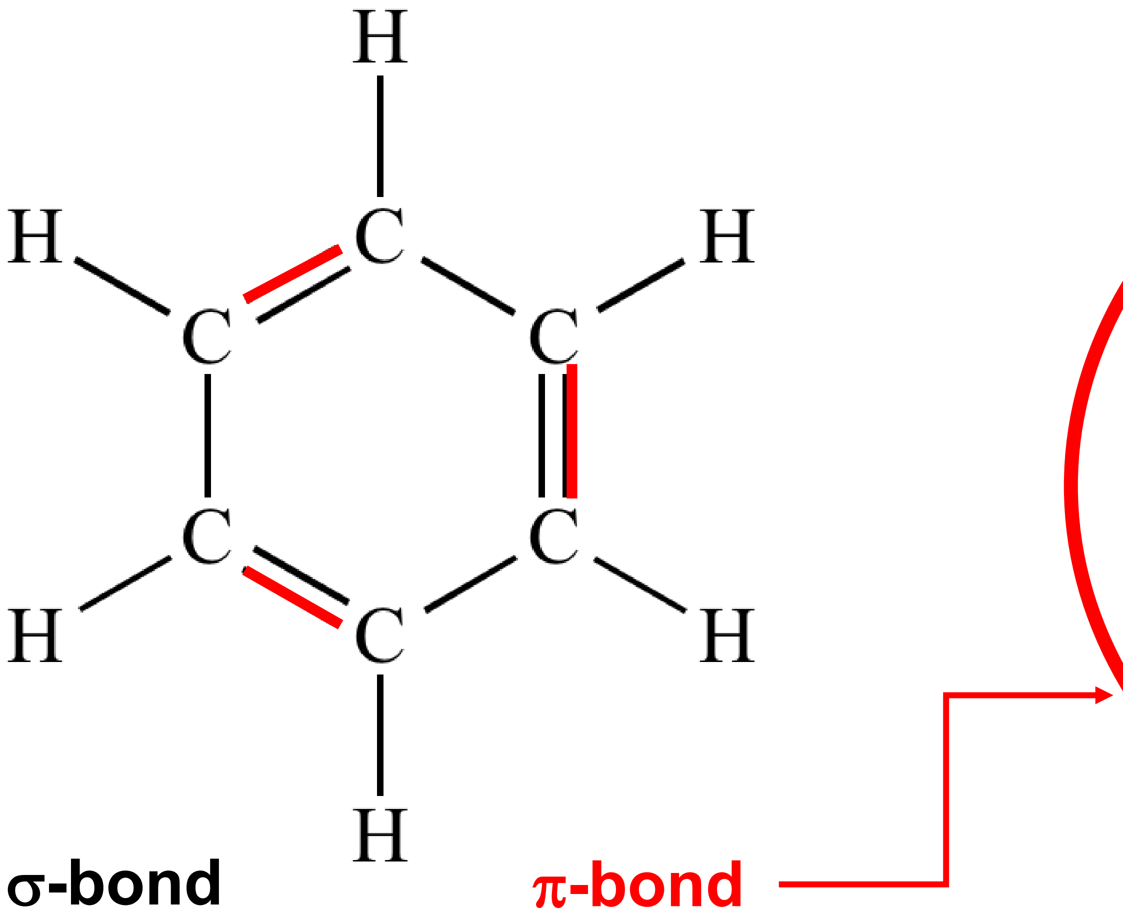




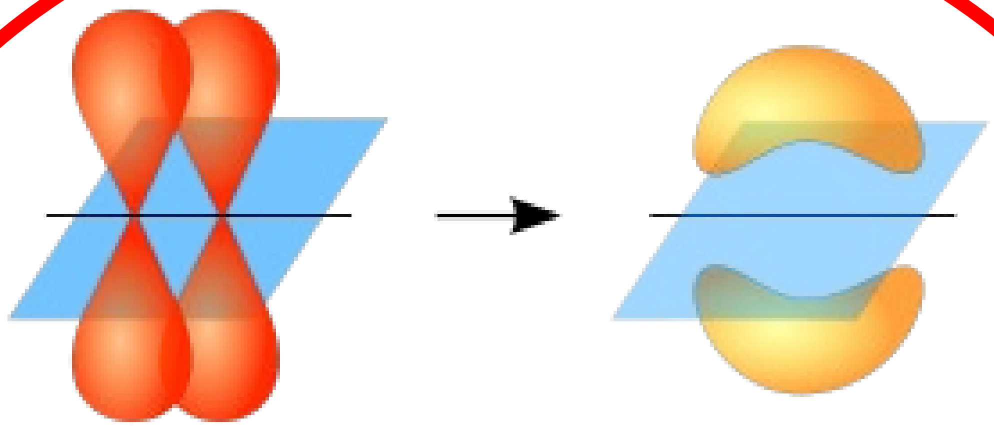
- 2 hybrid orbitals + 2 p-orbital
- 2 σ-bonds + 2 π-bond
- Linear
- Example: acetylene
- **Fluorescence**

Organic compounds: the π-bond

The case of hybrid sp^2 orbital: Benzene



π-bond



- The electrons which don’t participate to the hybrid orbitals form a π-bond;
- They are loosely bonded with the molecule; form a cloud above its plane

Emission and absorption spectra

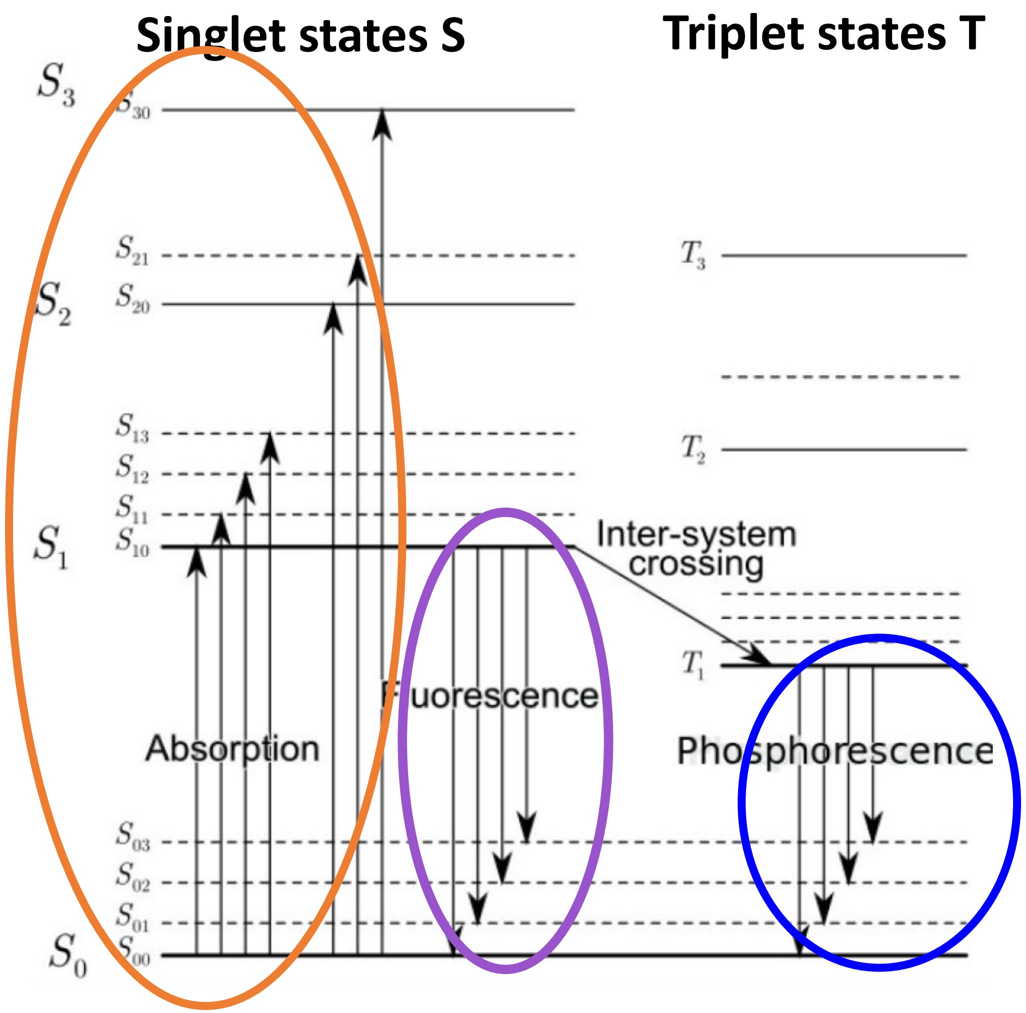
Flluorescence in the scintillators depends on the levels of the π-state

Fluorescence Emission (fast~ nsec)
Transition between $S_{10} \rightarrow S_{0k}$

Delayed fluoresce Emission (slow~100 nsec)
Transition between $T_1 \rightarrow S_{jk}$ followed by $S_{10} \rightarrow S_{0k}$

Phosphorescence Emission (very slow ~ >100 µs)
Transition between $T_1 \rightarrow S_{0k}$

Absorption
Transition between $S_{00} \rightarrow S_{jk}$



Emission and absorption spectra

Emission spectrum and self-absorption

- All organic molecules which have π-bond levels are potential scintillators;
- If the emission and absorption spectra overlap too much, the scintillator is inefficient;
- For this reason, organic liquid scintillators are always bynary or ternary mixtures

Solvent

- Particles deposit their energy and excites solvent molecules;
- **Problem:** self-absorption+non-optimal coupling with QE PMT

+

Fluor 1 (concentration ~ g/l)

- Fluor 1 absorption spectrum overlapped with the solvent emission spectrum;
- Emission spectrum at higher wavelenght with respect to the solvent;

➢ **Minimize absorption**

+

Fluor 2 (concentration ~ mg/l)

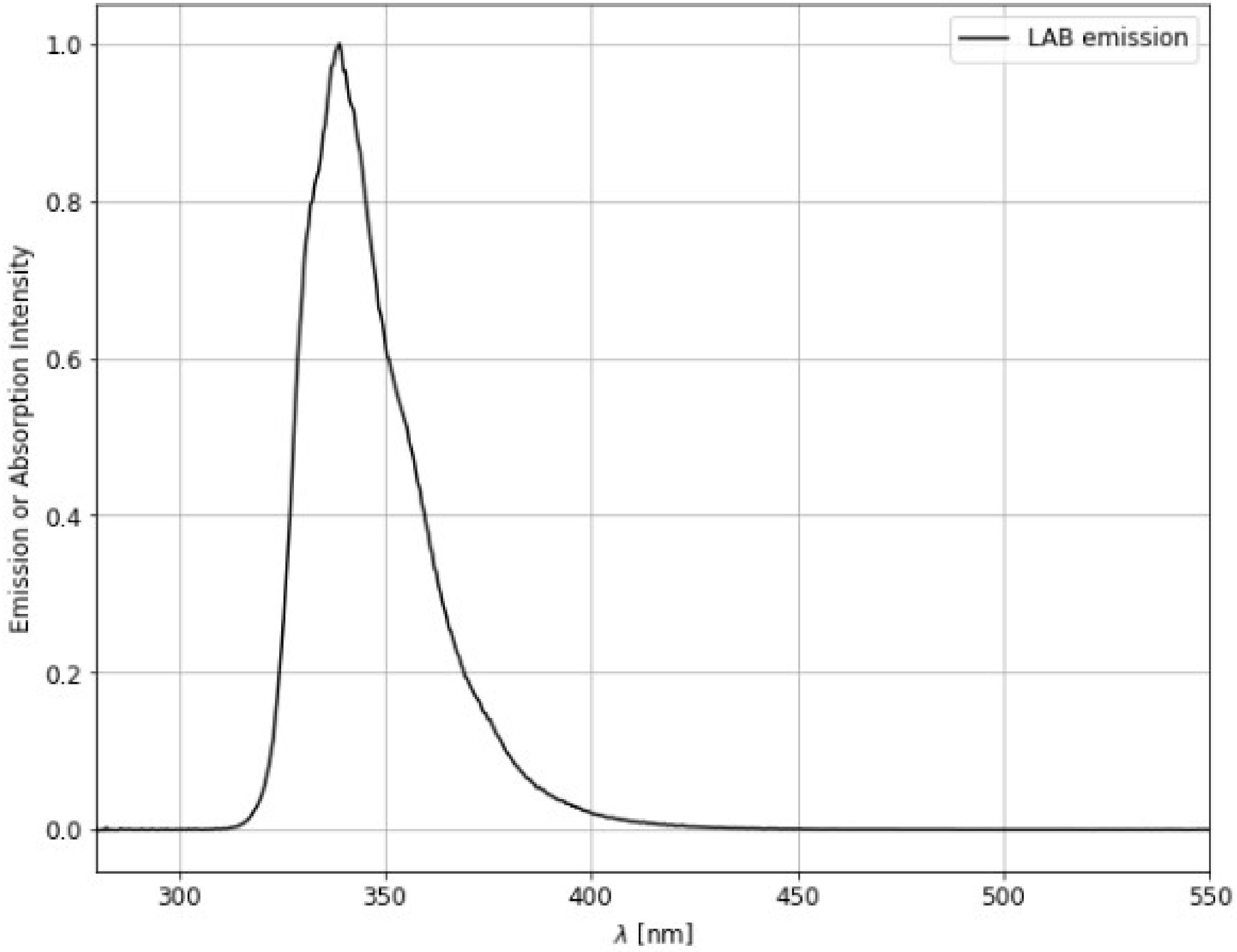
- Fluor 2 absorption spectrum overlapped with the Fluor 1 emission spectrum;
- Emission spectrum at higher wavelenght with respect to Fluor 1;

➢ **Minimize absorption + match with the PMT QE**

Emission and absorption spectra

An example: the JUNO liquid scintillator LAB + 2.5 g/l PPO + 3 mg/l bis-MSB

The solvent:
LAB



Emission and absorption spectra

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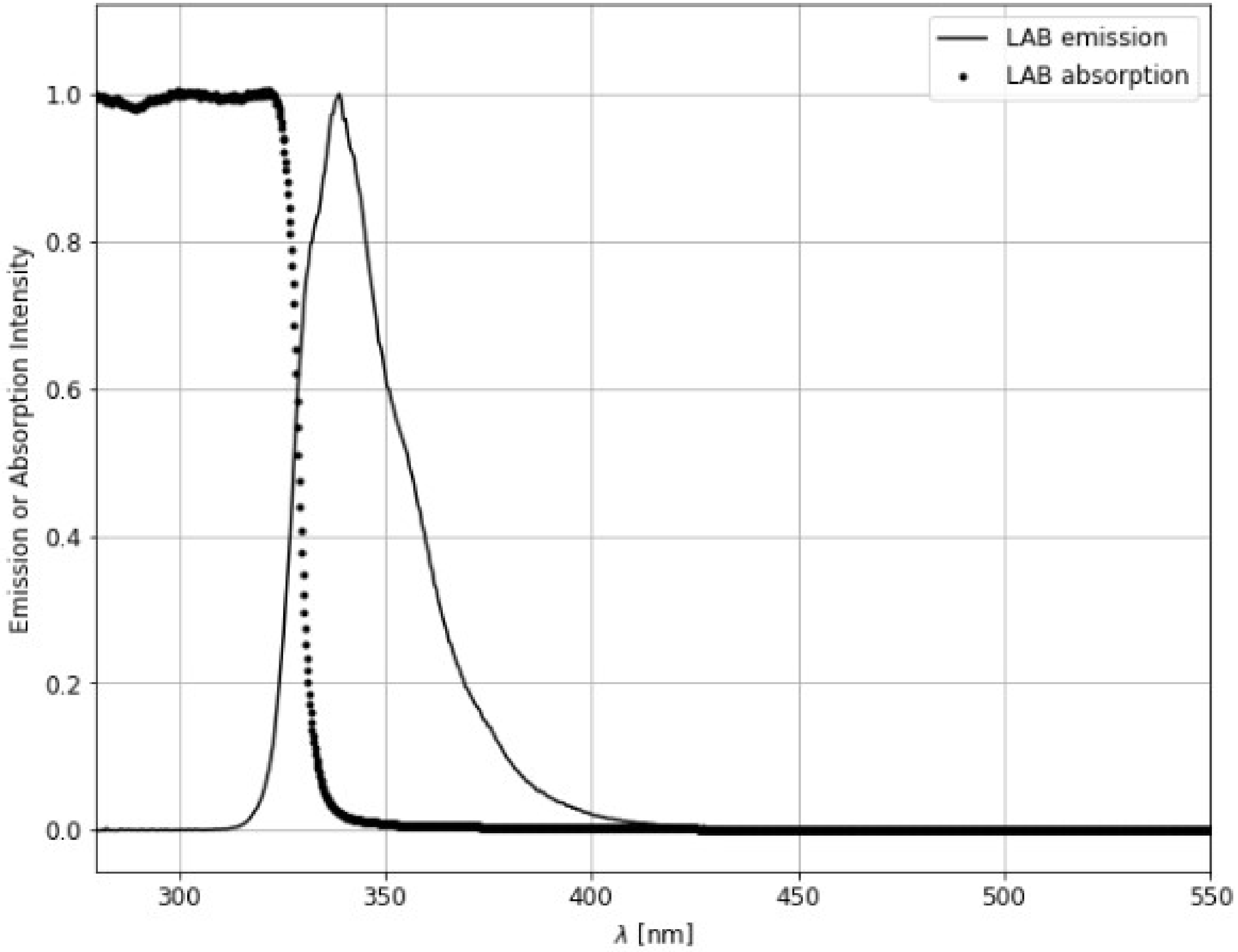

Emission and absorption spectra

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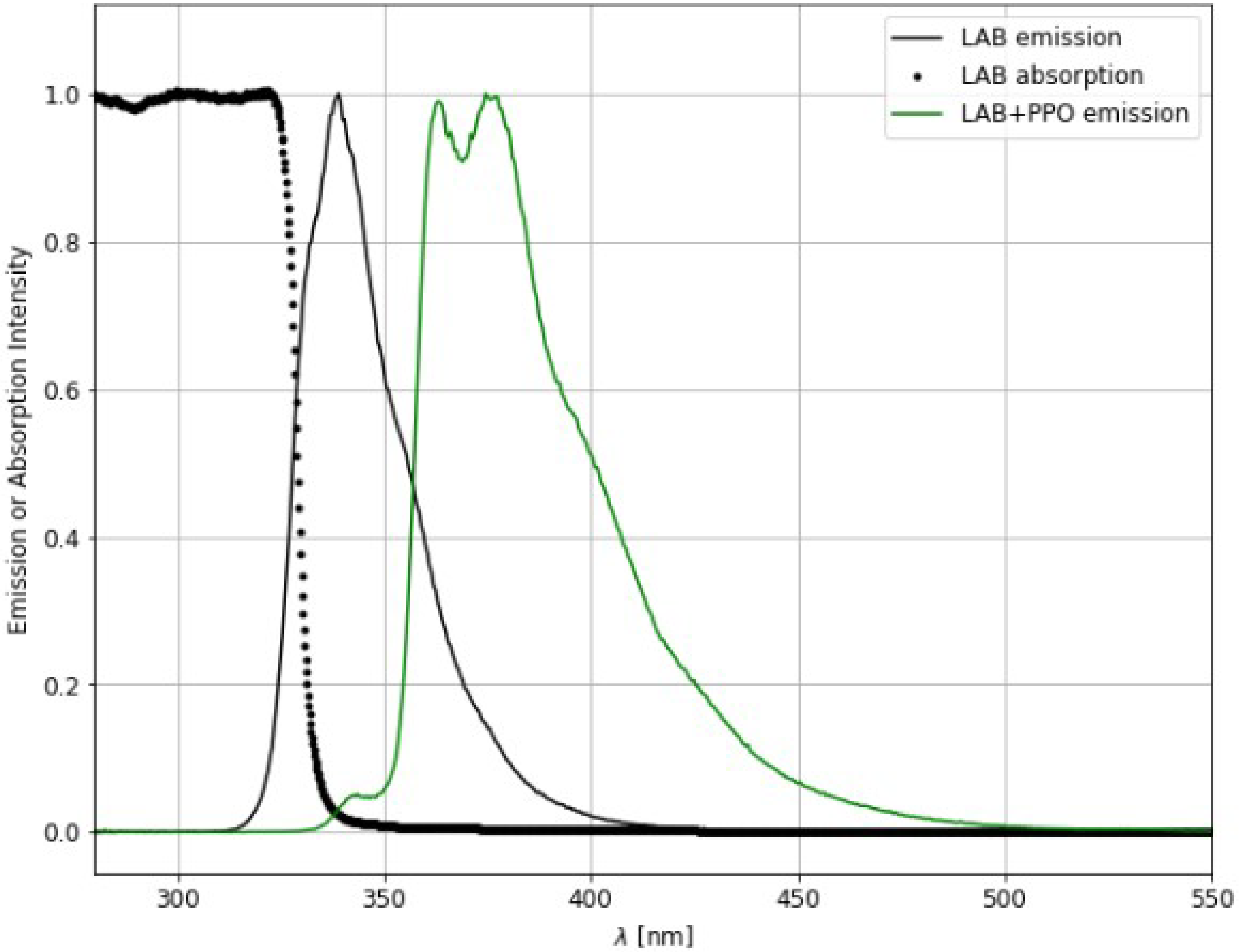
The solvent: LAB

Fluor 1: PPO



Emission and absorption spectra

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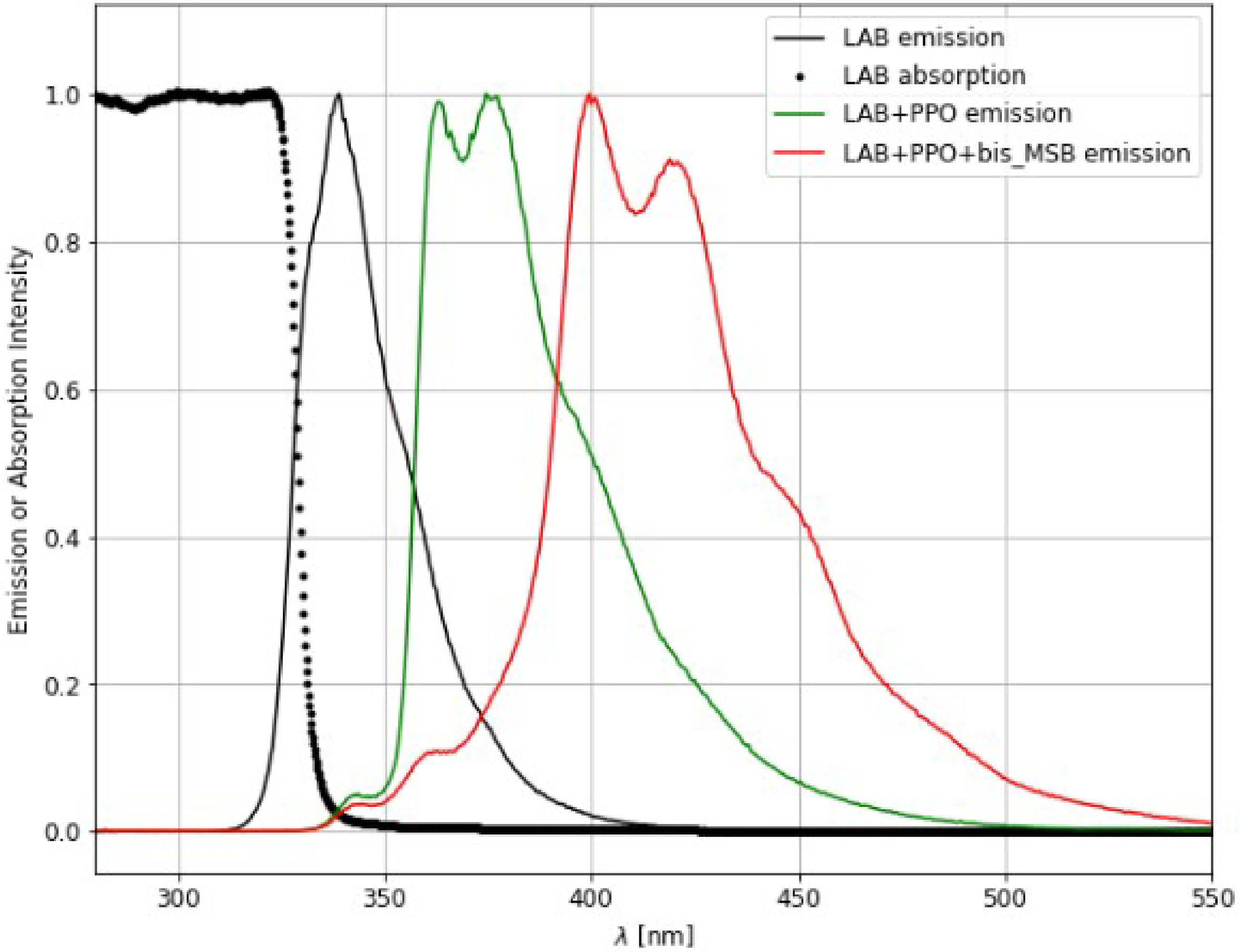
The solvent: LAB

Fluor 1: PPO

Fluor 2: bis-MSB



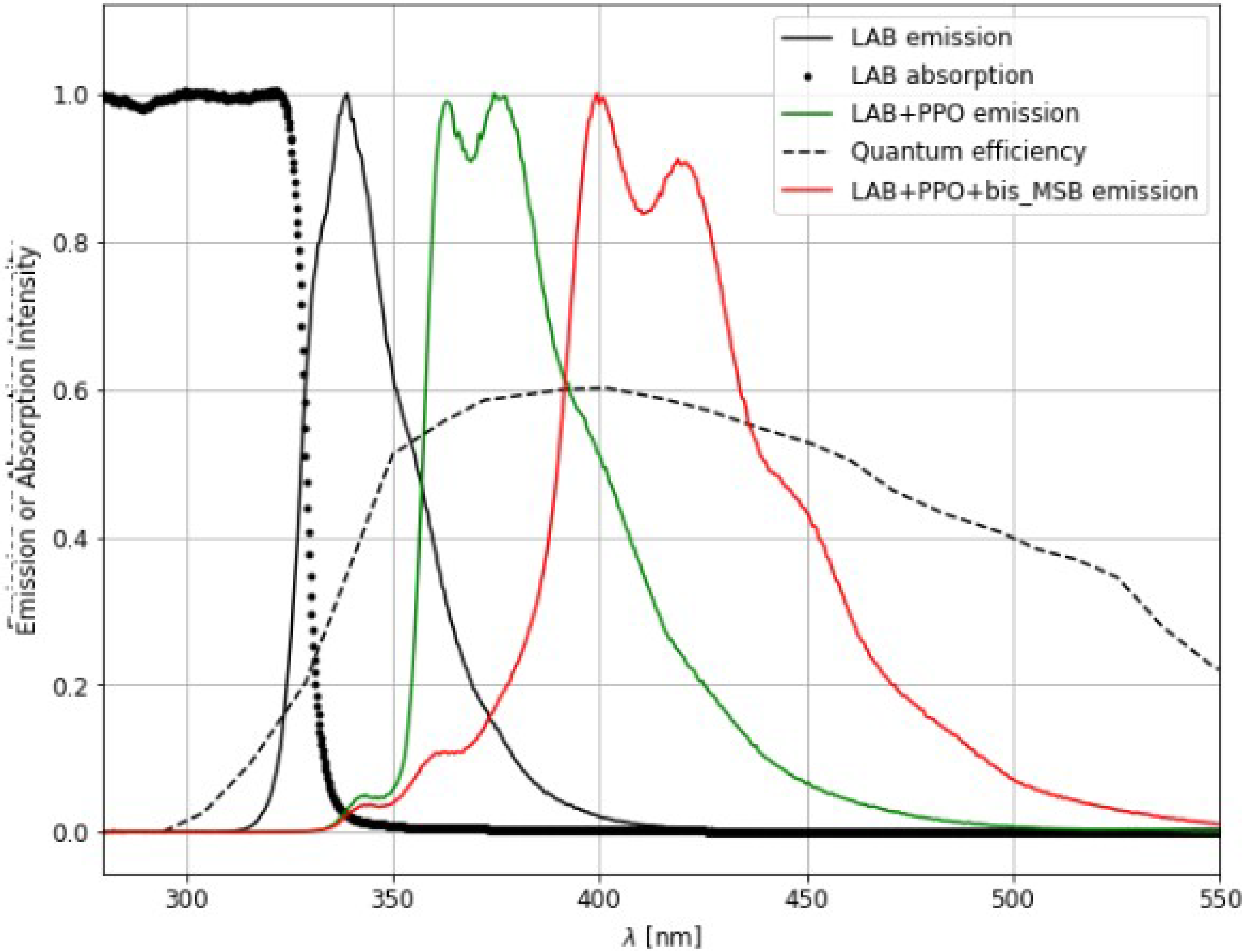
Emission and absorption spectra

An example: the JUNO liquid scintillator LAB + 2.5 g/l PPO + 3 mg/l bis-MSB

The solvent: LAB

Fluor 1: PPO

Fluor 2: bis-MSB



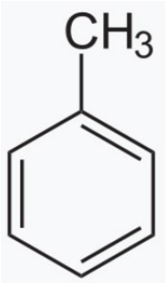
Examples of organic liquid scintillators

Some examples of solvents

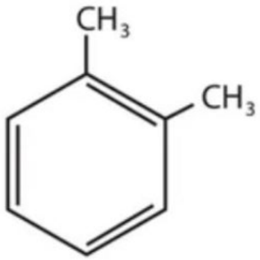
- Studies to identify the best aromatic organic compounds to be used as solvents in the liquid scintillator mixture started back in the 50s- 60s;

First generation solvents (50s- 60s)

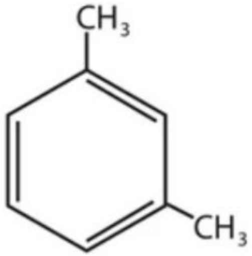
Highly flammable and hazardous for environment



toluene



Ortho-xylene



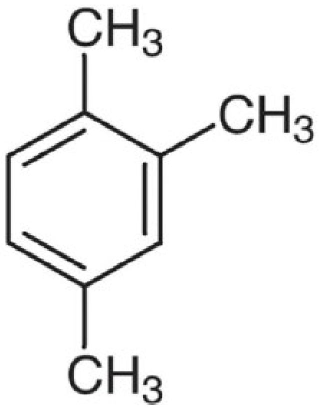
Meta-xylene

Para-xylene

Second generation solvents (70s)

Less toxic and less hazardous

Pseudocumene
(1,2,4- trimethylbenzene)
BX, KamLAND

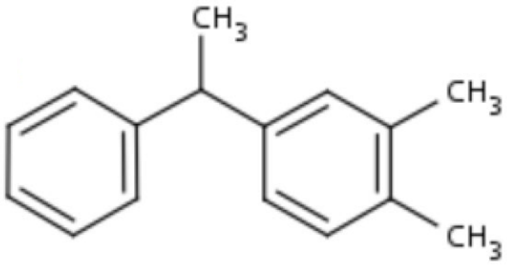


Examples of organic liquid scintillators

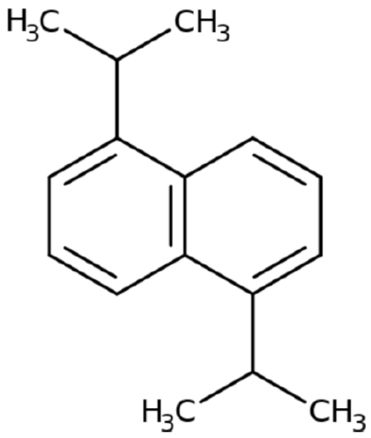
Current generation solvents

- Underground experiments require large masses of scintillating material;
- Current generation solvents are chosen to minimize hazards for safety and environment;
- Requirement: high flash point (not flammable), low vapour pressure, no odor, low toxicity, biodegradability;

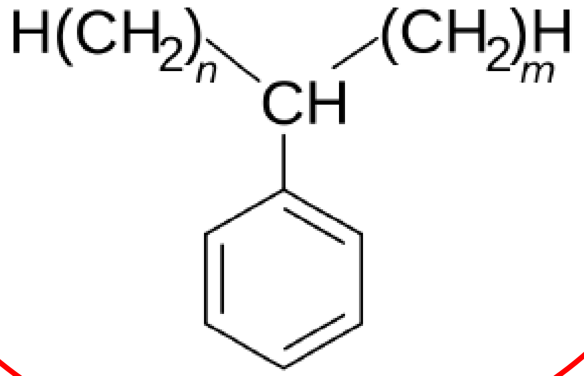
Phenyl xylyl ethane (PXE)



Diisopropylnaphtalene (DIN)

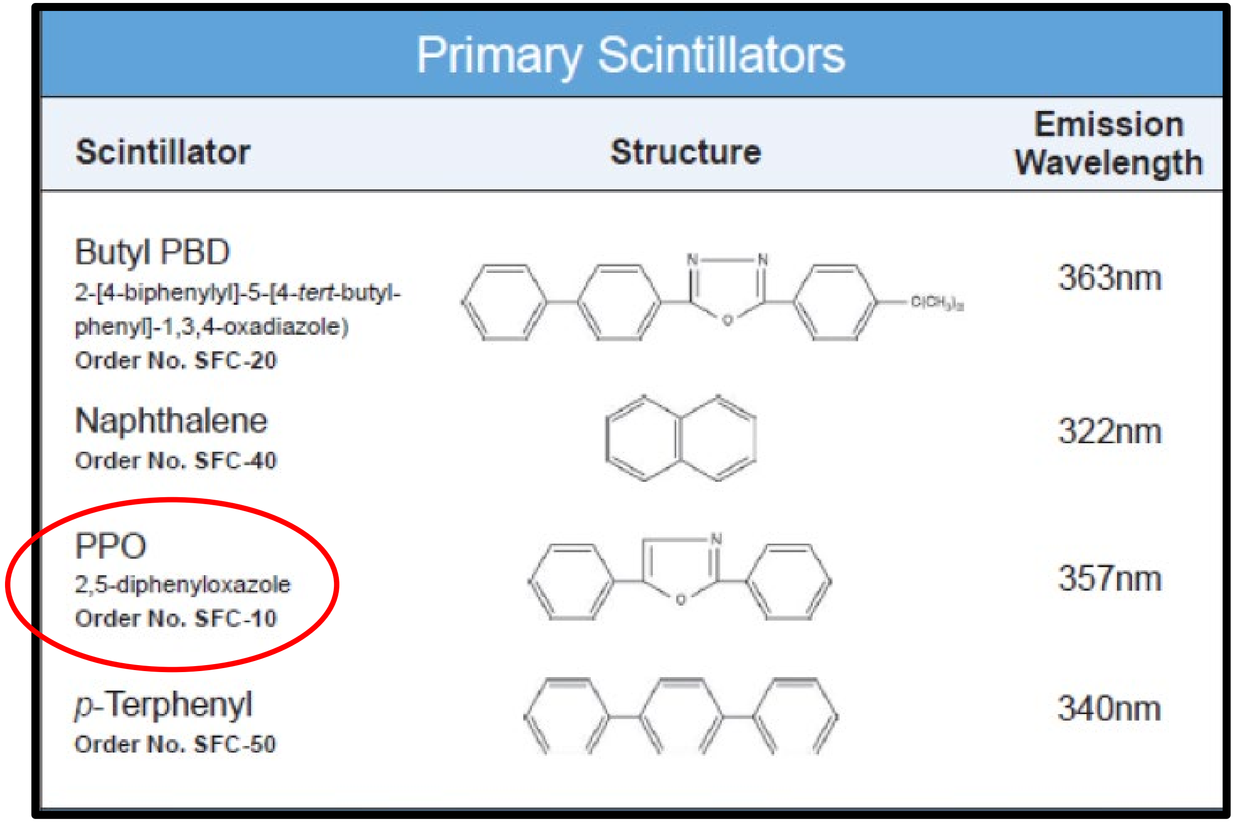


Linear alkylbenzene (LAB)



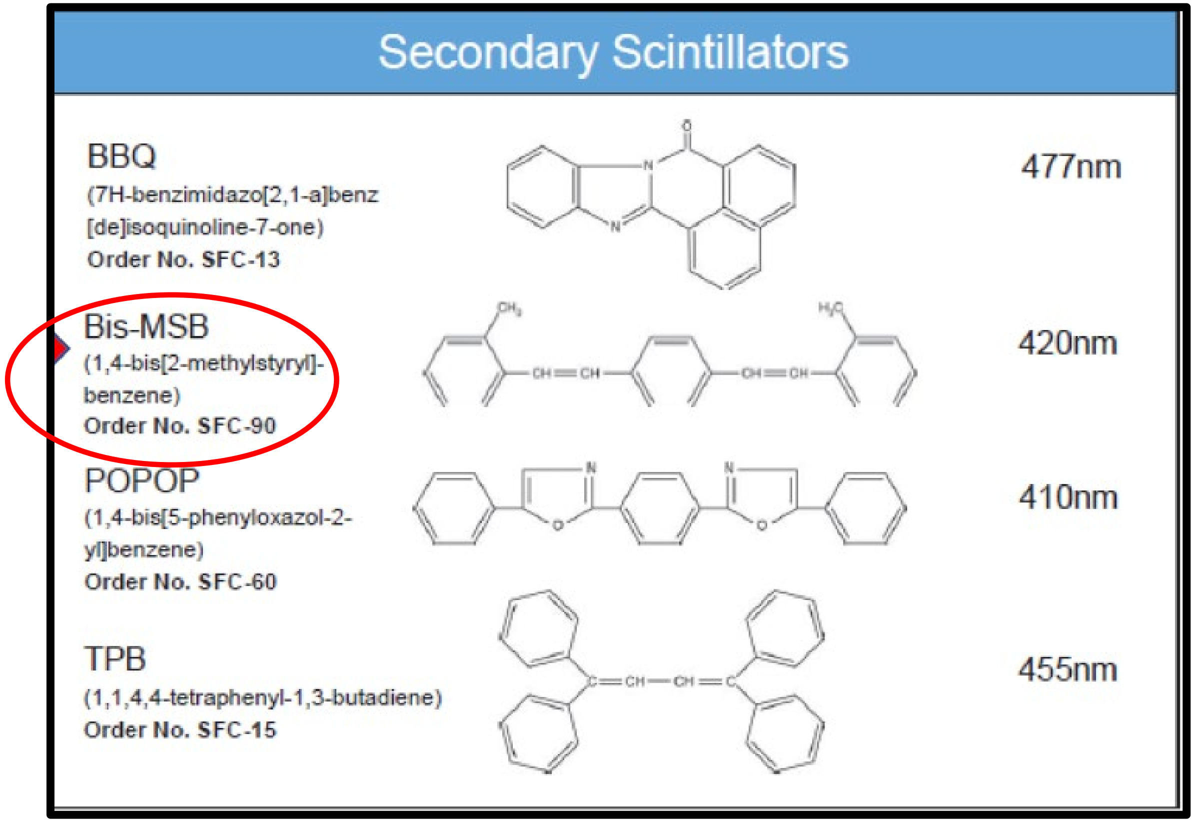
Examples of organic liquid scintillators

Some examples of solutes



Primary Scintillators

Scintillator	Structure	Emission Wavelength
Butyl PBD 2-[4-biphenylyl]-5-[4-*tert*-butyl-phenyl]-1,3,4-oxadiazole) **Order No. SFC-20**		363nm
Naphthalene **Order No. SFC-40**		322nm
PPO 2,5-diphenyloxazole **Order No. SFC-10**		357nm
p-Terphenyl **Order No. SFC-50**		340nm



Secondary Scintillators

BBQ (7H-benzimidazo[2,1-a]benz[de]isoquinoline-7-one) **Order No. SFC-13**		477nm
Bis-MSB (1,4-bis[2-methylstyryl]-benzene) **Order No. SFC-90**		420nm
POPOP (1,4-bis[5-phenyloxazol-2-yl]benzene) **Order No. SFC-60**		410nm
TPB (1,1,4,4-tetraphenyl-1,3-butadiene) **Order No. SFC-15**		455nm

Most popular: PPO with a concentration of few g/l

Most popular: bis-MSB with a concentration of few mg/l

Where do we find organic liquid scintillators?

Where do we find organic liquid scintillator?

Neutrino Oscillations

- Accelerator neutrinos (LSND, NOVA, THEIA?) (E~ GeV)
- Reactor neutrino studies (CHOOZ, Double-Chooz, KAMLAND, Daya-Bay, RENO, JUNO) (E~0-10 MeV)

Neutrinos from natural sources

- Solar neutrinos (Borexino) (E~ MeV)
- Supernova neutrinos (LVD) (E ~0-50 MeV)

Investigate the nature of neutrinos (Mayorana or not?)

- Double Beta Decay (SNO+, Kamland Zen) (E~MeV)

Neutrino Physics (see Lessons by Marco Pallavicini on Monday)

Dark Matter Search (mainly as veto counters)

- SABRE South (Australia)
- COSINE-100 (Korea)

Requirements for underground experiments

RARE EVENTS

- Large Masses
- Long data-taking (stability in time)

Background Control

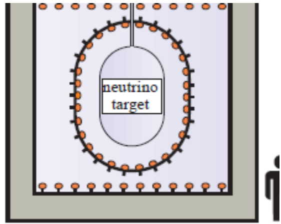
- Underground facilities
- Shielding Strategy
- Veto system
- Radiopurity

Info for each event

- Count signal events
- Measure energy
- Measure position of interaction
- Measure direction

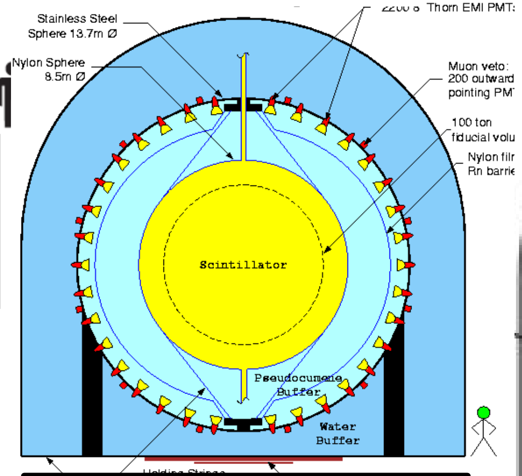
Typical geometry: un-segmented detectors

Reactor ν 90’s



CHOOZ
M~5t

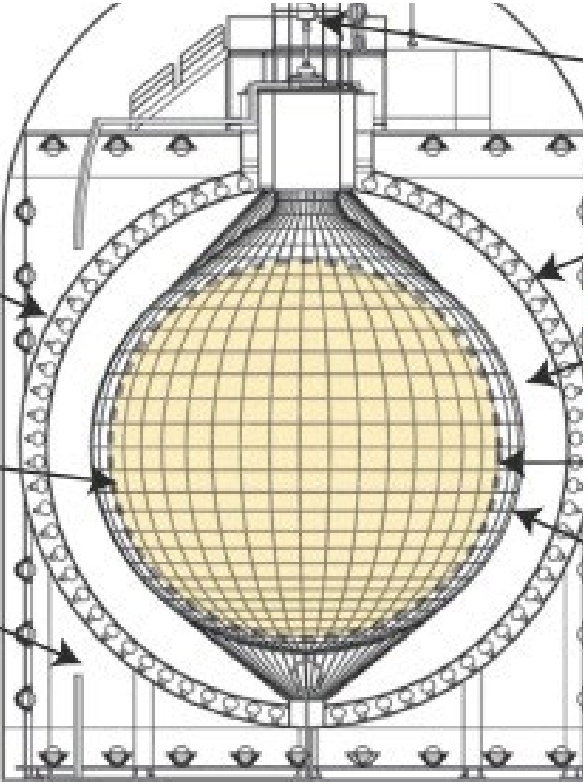
Solar ν 2007-2021



Borexino
M~300t

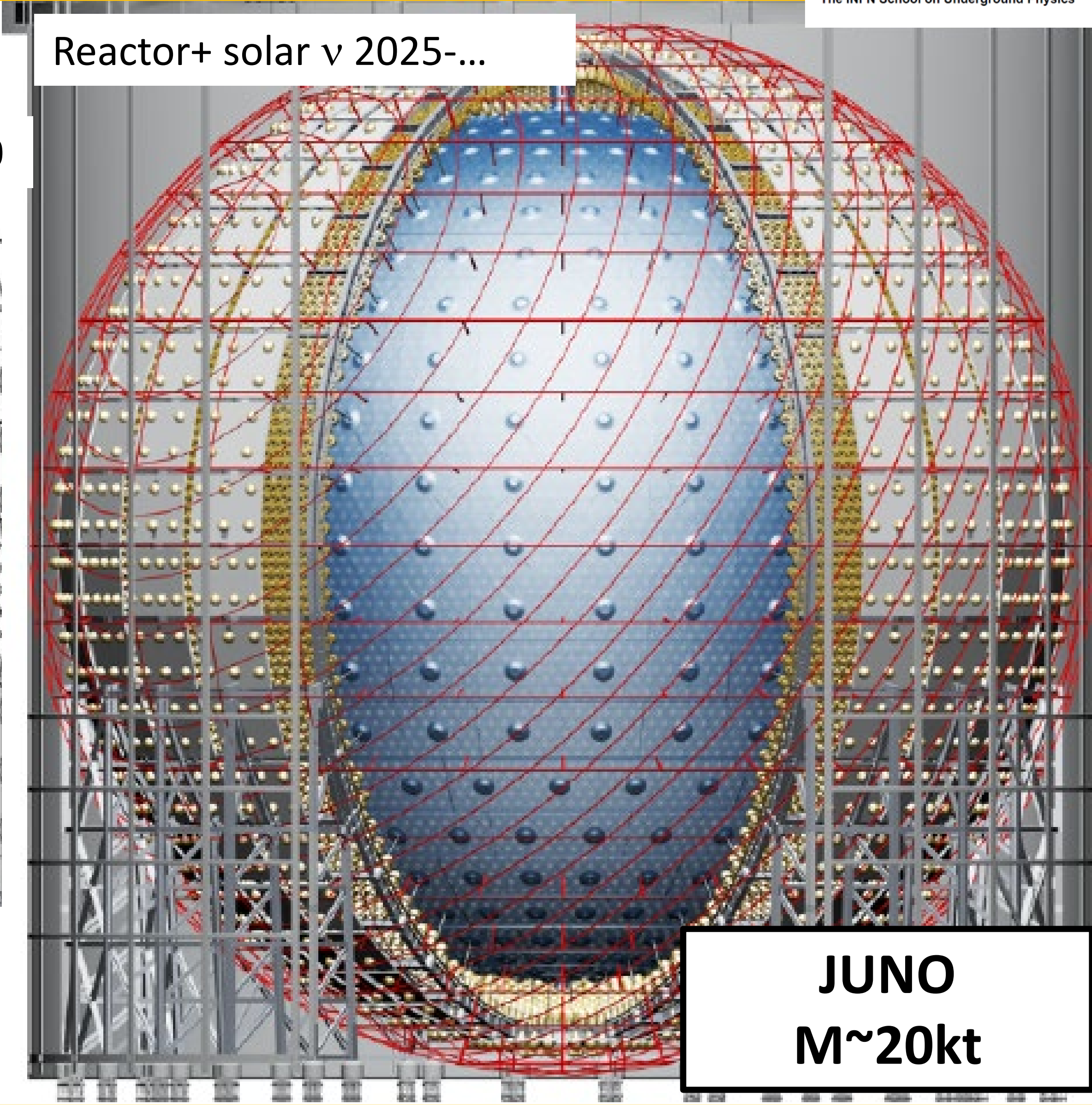
Time

Reactor+ solar ν 2002-2010



Kamland
M~1kt

Reactor+ solar ν 2025-…



JUNO
M~20kt

Typical geometry: un-segmented detectors

1^{st} example: Borexino (solar neutrinos)

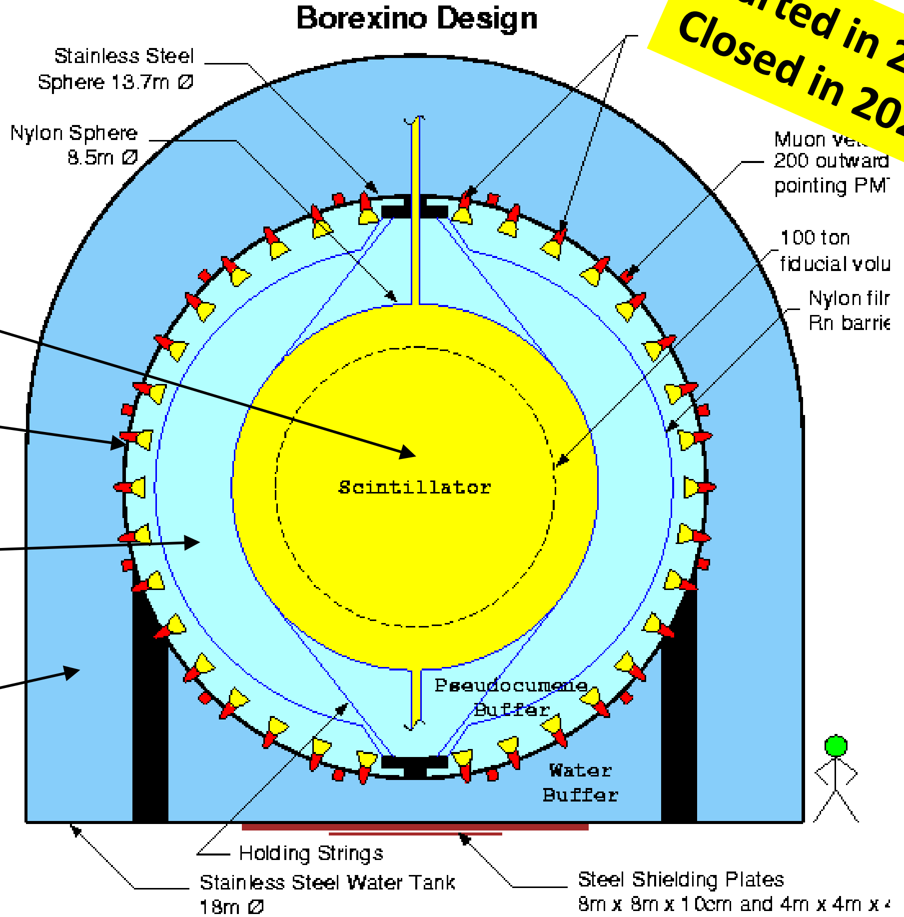
Core of the detector: 300 tons of liquid scintillator (PC+PPO) contained in a nylon vessel of 4.25 m radius;

2214 photomultiplier tubes pointing towards the center to view the light emitted by the scintillator;

Buffer liquid: 1000 tons of non-scintillating buffer liquid to shield from PMT radioactivity

External shielding: 1000 tons of water to shield from external radioactivity

Characteristic ''onion-like'' structure to protect the core from radioactivity



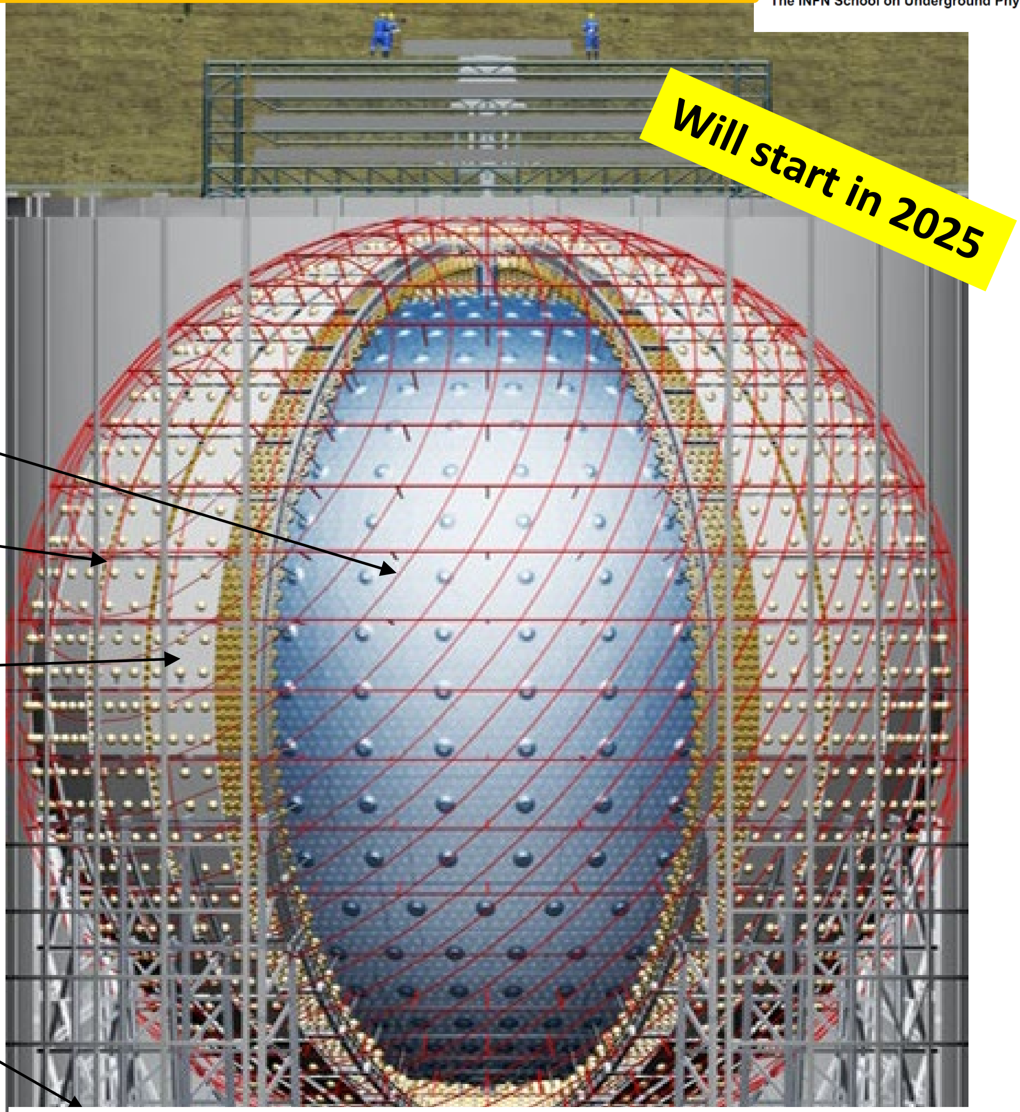
Started in 2007
Closed in 2021

@ Laboratori Nazionali del Gran Sasso (Italy)

Typical geometry: un-segmented detectors

SoUP
The INFN School on Underground Physics

2nd example: JUNO (reactor, solar..)



Core of the detector: 20ktons of liquid scintillator (LAB+2.5g/lPPO+ 3 mg bis-MSB) contained in an acrylic vessel of 35 m diameter;

43000 photomultiplier tubes pointing towards the center to view the light emitted by the scintillator;

Buffer liquid: water as a buffer to shield from PMT radioactivity

External shielding: 35 ktons of water to shield from external radioactivity

Characteristic ''onion-like'' structure to protect the core from radioactivity

Guandong Province (South China)

Detecting reactions

- **Neutrinos** (either solar or Supernova) are seen mainly by their scattering on electrons:

$$\nu_x + e^- \rightarrow \nu_x + e^- \text{ (ES)}$$

- If the detector is big, there are sufficient ^{13}C in the scintillator to also have these reactions:

$$\nu_e + {}^{13}C \rightarrow e^- + {}^{13}N \quad \text{(CC)}$$
$$\nu_x + {}^{13}C \rightarrow \nu_x + {}^{13}C \quad \text{(NC)}$$

- **Anti-neutrinos** (reactor, geo-neutrinos or Supernova) are detected with the reaction:

$$\overline{\nu}_e + p \rightarrow e^+ + n \quad \text{(IBD)}$$

Two signals in coincidence

1. e+ (prompt)
2. Neutron is captured and produces 2.2 Mev γ (delay)

The products of the interaction deposit their energy in the scintillator which produces light

Typical geometry: un-segmented detectors

3rd example: SNO+ (Neutrinoless Double Beta Decay)

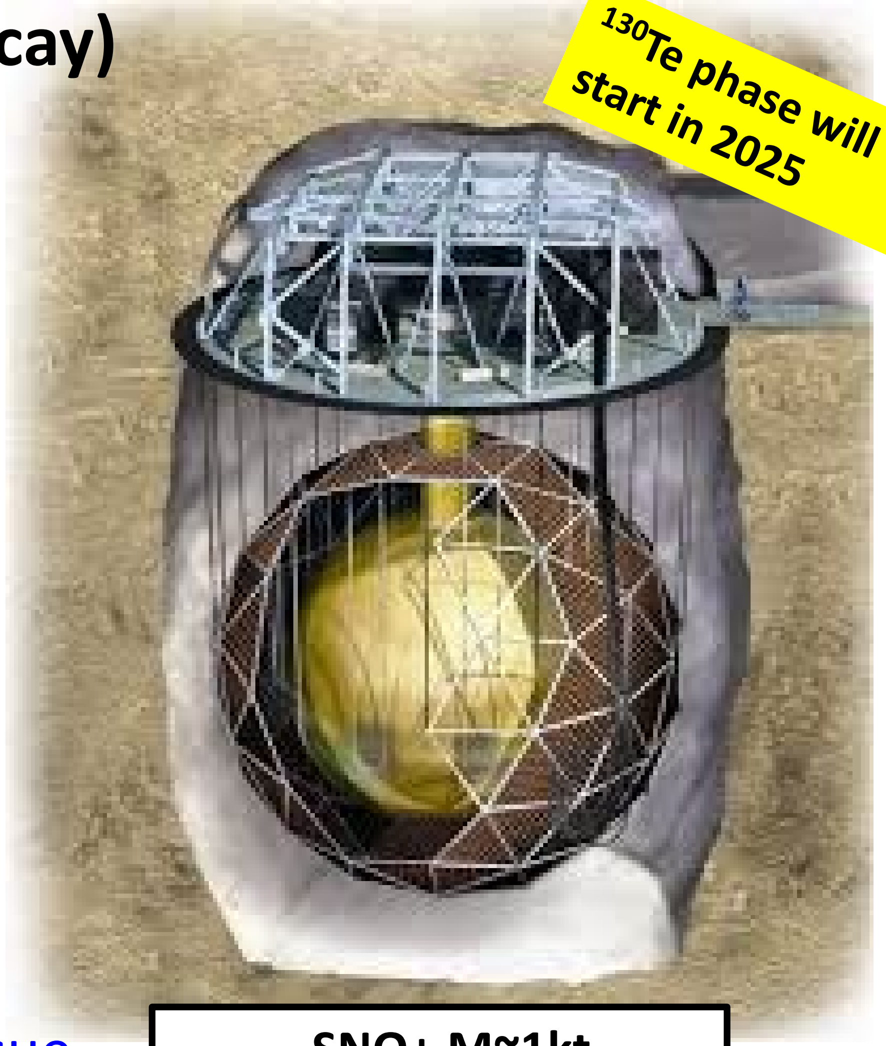
Search for Neutrinoless Double Beta Decay (0ν– ββ)

- Loading the liquid scintillator with a DBD candidate;
- Calorimetric measurement of the 2 electrons emitted in the decay;

^{130}**Te → ^{130}Xe + 2β-** (Q_{value} ~2.5 MeV)

- Scintillator LAB+2 g/l PPO + 20ml/l bis-MSB;
- Tellurium loaded at 0.5% (by weight)
- 3.9 tons of natural Tellurium
- 1.3 ton of ^{130}Te;

➢ Transparency and stability of the scintillator can be an issue



^{130}Te phase will start in 2025

SNO+ M~1kt

Typical geometry: un-segmented detectors

3rd example: KamLAND-Zen (Neutrinoless Double Beta Decay)

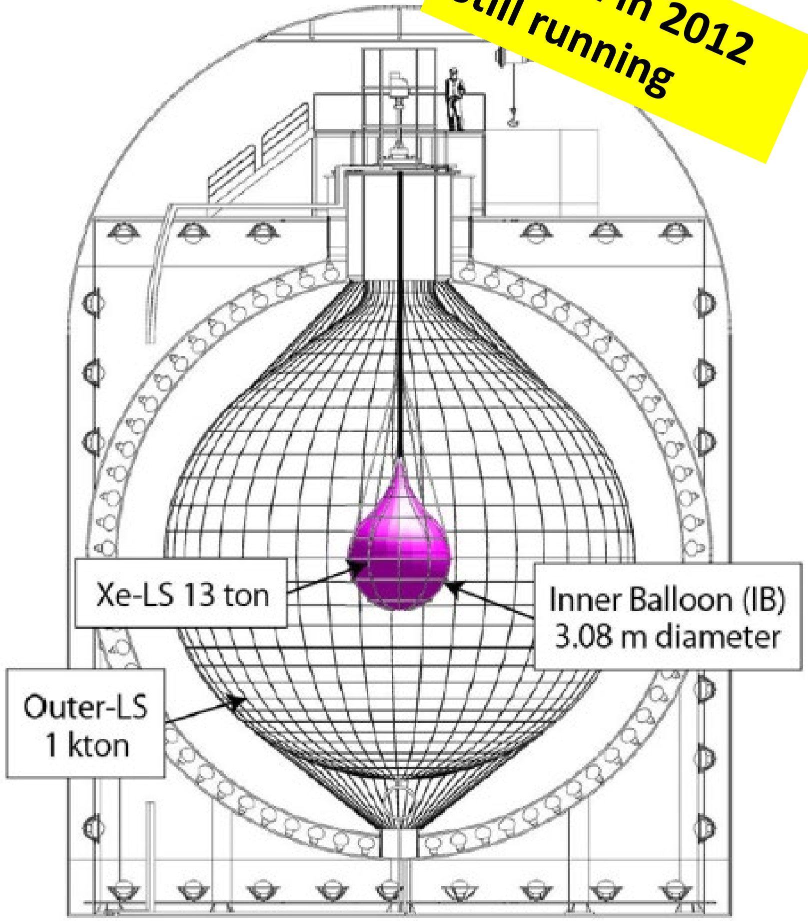
Started in 2012
Still running

Search for Neutrinoless Double Beta Decay (0ν– ββ)

- Loading the liquid scintillator with a DBD candidate;
- Calorimetric measurement of the 2 electrons emitted in the decay;

$^{136}\mathbf{Xe} \rightarrow {}^{136}\mathbf{Ba} + 2\beta^-$ (Q_{value} ~2.5 MeV)

- Decane(82%)+pseudocumene(18%)+2.7 g/l PPO;
- Baloon R=3 m with scintillator+Xenon (2.5% by weight)
- Total Xenon mass= 320 Kg (enriched 90% in ^{136}Xe)



Kamland-Zen M~1kt

Radiopurity of liquid scintillators

RARE EVENTS →

- Large Masses
- Long data-taking (stability in time)

Background Control →

- Underground facilities
- Shielding Strategy
- Veto system
- Radiopurity

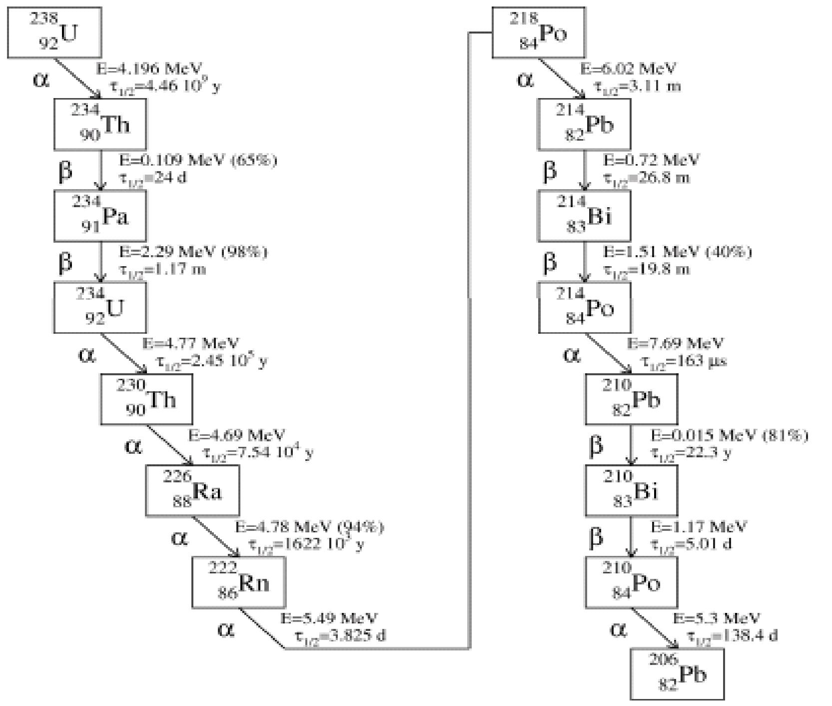
Info for each event →

- Count signal events
- Measure energy
- Measure position of interaction
- Measure direction

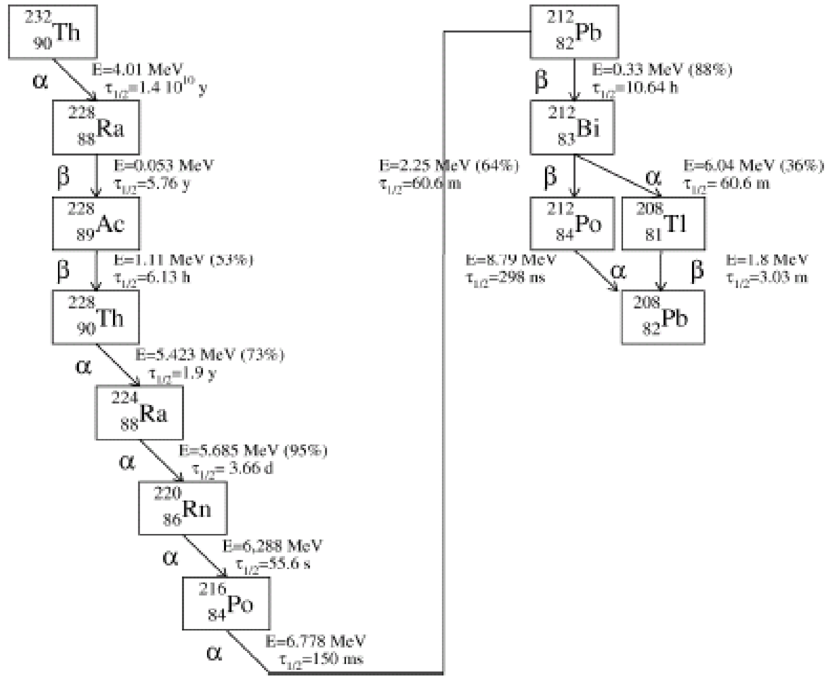
Radiopurity of liquid scintillators: U, Th, K, Kr

Typical contaminants that are present in all materials are:

- Metallic impurities: ^{238}U and ^{232}Th chain, ^{40}K
- Ambient noble gases: ^{222}Rn (Radon), ^{85}Kr, ^{40}Ar



^{238}U chain



^{232}Th chain

α, β, γ

(~ 0–3 MeV)

Radiopurity of liquid scintillators: U, Th, K, Kr

- Organic liquids tend to have very low levels of radioactive background impurities;
- In fact, ionic impurities (like U, Th and K) do not dissolve easily in a non-polar medium;

In Borexino these contaminans have been further reduced by a combination of:

- **Filtration:** ~ 0.05 mm teflon filters to remove particulate;
- **Water extraction:** counter current flow of distilled water for removal of metal and ionic impurities;
- **Distillation:** Vacuum distillation to remove low volatility species. Removes metal impurities and improve optical quality;
- **Nitrogen Stripping:** counter current flow of nitrogen gas to remove dissolved water and gaseous impurities (for example, Radon and Kripton)
- **Fluor pre-purification:** water extraction of concentrated solution of solvent and solute for removal of metal and ionic impurities

Radiopurity of liquid scintillators: U, Th, K, Kr

Φ (solar ν)~6.6 x 10^{10} $\nu/cm^2/sec$

In a typical scintillator, using $\nu + e^- \rightarrow \nu + e^-$ (with no threshold) the rate of interaction is

Rate (solar ν)~2 events/day/ton

- EXAMPLE: The radioactivity in U, Th and K of common drinking water is approximately 10 Bq/Kg → N~10^9 event/day/ton (equivalent to 6×10^{-8} g/g)
- A liquid scintillator starts already with a much lower level of radioactivity and can be brought down to ~10^{-17} g/g (KamLAND) or even lower 10^{-19} g/g - 10^{-20} g/g (Borexino)

For 10^{-17} g/g → Rate (^{238}U)~0.2 events/day/ton

Radiopurity of liquid scintillators: U, Th, K, Kr

HOWEVER…some of the isotopes of the 238U chain may be present out of equilibrium

^{222}Rn is a gas and can enter due to air-leak;

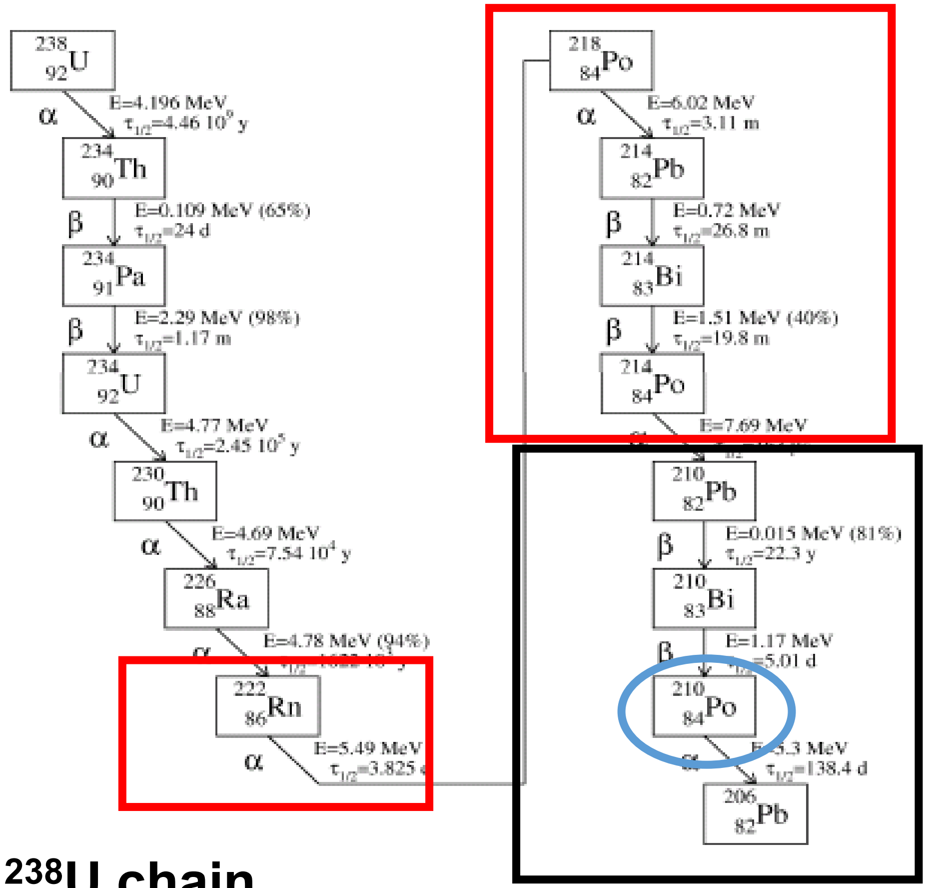
- it decays in ~5 days
- Produces a transient contamination of ^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po;

^{210}Po is present on metallic surfaces and can be washed out by the scintillator;

- it decays in ~ 200 days

^{210}Pb is often found out of equilibrium;

- It decays in ~ 30 years;
- Produces a long term contamination of ^{210}Po and ^{210}Bi



^{238}U chain

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^{210}**Po** is present on metallic surfa

washed out by the scintill

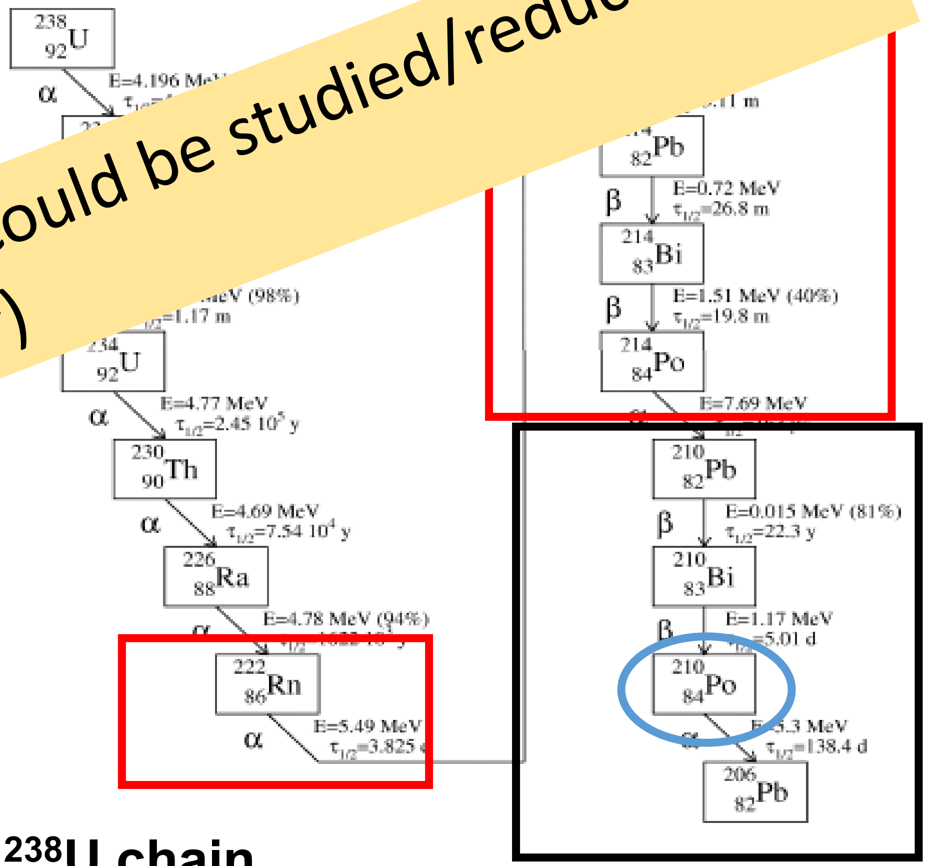
- it decays in ~ 2

^{210}Pb

of equilibrium;

- 30 years;
- a long term contamination of ^{210}Po and ^{210}Bi

N.B.: A lot of this background is alpha decay → could be studied/reduced with alpha/beta discrimination techniques (See later)



^{238}U chain

Radiopurity of liquid scintillators: ^{14}C

- ^{14}C is an irreducible contaminant of an organic liquid scintillator
- It decays $\beta-$ with an end-point of 156 keV;

Its natural abundance is 1 atom of ^{14}C over 10^{12} atoms of ^{12}C;

→ Rate(^{14}C)= 10^{10} event/ton/day !

Fortunately, organic liquid scintillators are derived from petrol which have stayed for millions of years underground→

Abundance is ~ 1 atom of ^{14}C over 10^{17} – 10^{18} atoms of ^{12}C

→ Rate(^{14}C)= 10^4 - 10^5 event/ton/day

- Fortunately, all the ^{14}C events have low energy (<200 keV)→ eliminated with a threshold;
- **Problem of pile-up events (2 or more ^{14}C events falling in the same acquisition window)**

Requirements for underground experiments

RARE EVENTS

- Large Masses
- Long data-taking (stability in time)

Background Control

- Underground facilities
- Shielding Strategy
- Veto system
- Radiopurity

Info for each event

- Count signal events
- Measure energy
- Measure position of interaction
- Measure direction

Info for each event

Number of collected photons

Energy

$$\frac{\sigma(E)}{E} \sim \frac{3-5\ \%}{\sqrt{E}}$$

Time of arrival of collected photons @ each PMT

Position

$$\frac{\sigma(x)}{x} \sim \frac{10\text{–}20\ \text{cm}}{\sqrt{E}}$$

Pulse-shape discrimination

α, β^-, β^+

Energy reconstruction

Number of collected photons→ Energy reco

- **An organic liquid scintillator produces ~ 10000 photons/MeV (Light Yield);**
- This is a relatively large number (compared to Cherenkov detectors for example)
- However, it is smaller than inorganic scintillating crystals (in NaI LY~ 40000 ph/MeV)

→ what really counts is the amount of detected photons N_{pe}!

$$\boxed{\mathbf{N_{pe}/MeV = LY \times GC \times QE(\lambda) X\ PE(\lambda)}}$$

- LY= Light Yield
- GC= Geometrical Coverage
- QE(λ) + Quantum Efficiency
- PE(λ) = Propagation Effects (absorption, re-emission, scattering...)

Number of collected photons→ Energy reco

Geometrical Effects

- Coverage of PMTs must be maximized to avoid loss of light simply because it doesn’t hit a PMT fotocatode

Quantum Efficiency

- Matching of the scintillator emission spectrum with QE

Propagation Effects

- Especially in large volume detectors the propagation effects are crucial
- Transparency of scintillator is an important parameter
- Probability of re-emission after absorption is also a crucial point
- Refraction index at the interface between materials (PMTs, vessel)

MonteCarlo simulations to describe all these effects are crucial both for the design of the experiment and also for data analysis

Number of collected photons→ Energy reco

Example 1: in Borexino

~10^4 ph/MeV

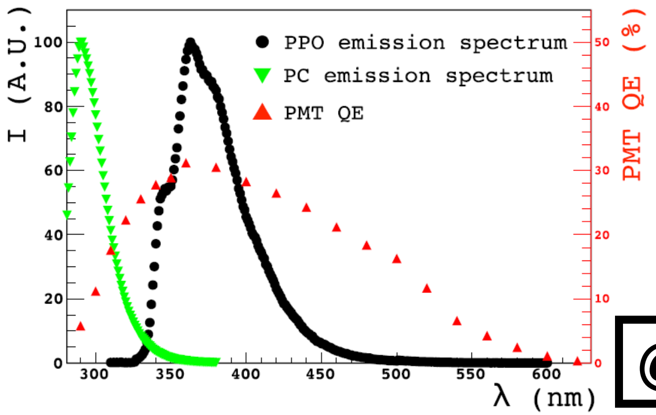
$$N_{pe}/\text{MeV} = \text{LY x GC x QE}(\lambda) \text{ x PE}(\lambda)$$

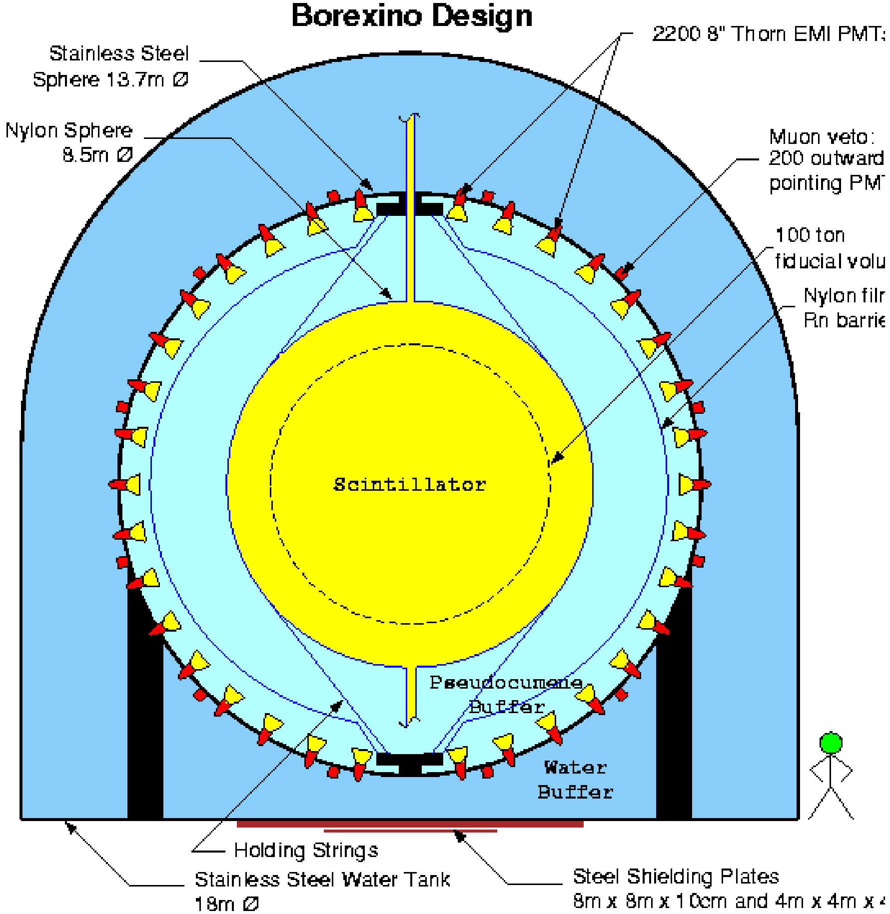
~30%

~30%
at peak

BX had around 500 p.e./MeV

$\sigma(E)/E$ ~ 5% (@1 MeV)





@ Laboratori Nazionali del Gran Sasso (Italy)

Number of collected photons→ Energy reco

Example 2: in JUNO

~10^4 ph/MeV

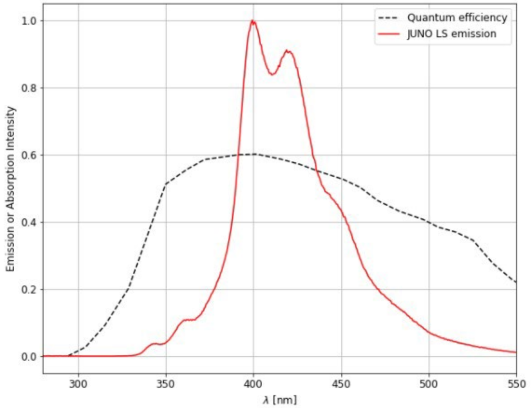
$$\boxed{N_{pe}/\mathrm{MeV} = \mathrm{LY} \times \mathrm{GC} \times \mathrm{QE}(\lambda) \times \mathrm{PE}(\lambda)}$$

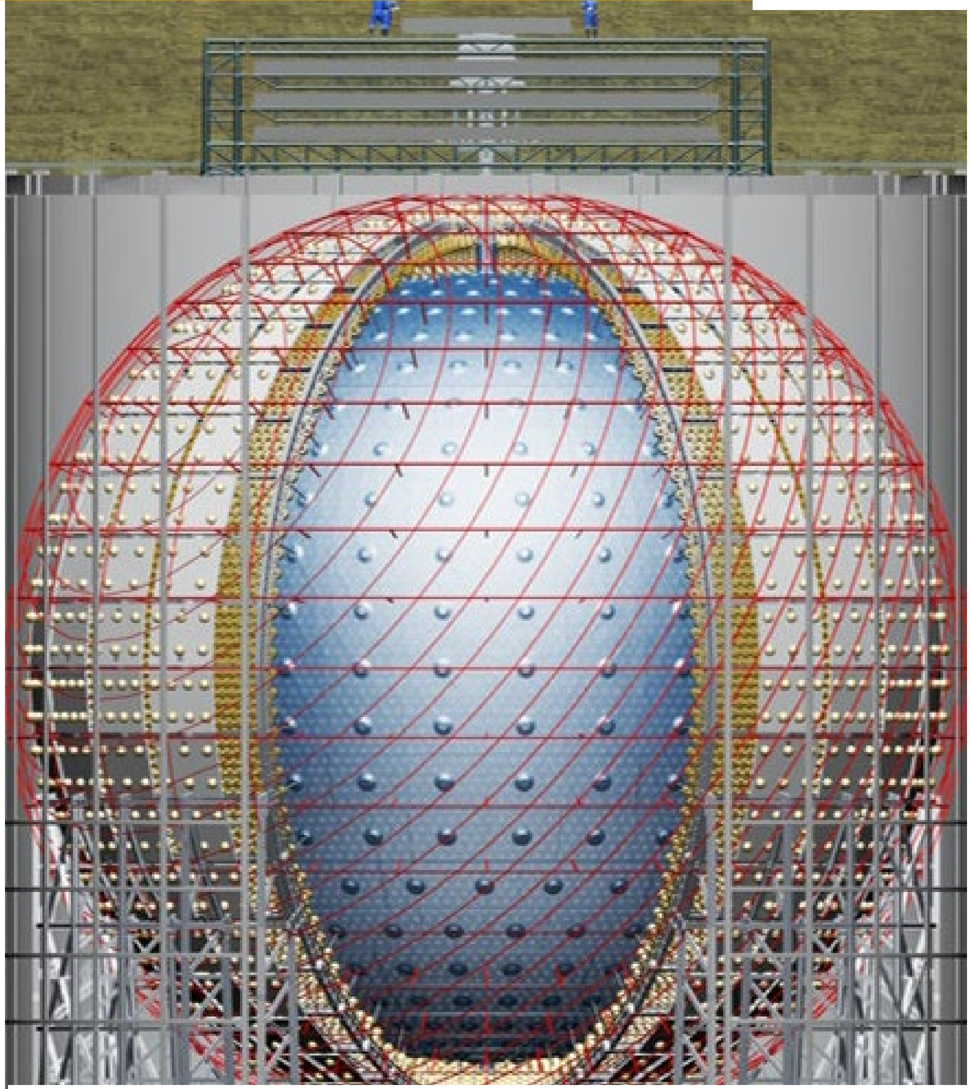
~78%

~30%
at peak

JUNO will have ~1600 p.e./MeV

$\sigma(E)/E$ ~ 3% (@1 MeV)





Guandong Province (South China)

Number of collected photons→ Energy reco

Ionization Quenching

If the scintillator response was linear → $E = k N_{pe}$

- ➢ From N_{pe} it would be possible to determine E if we know the proportionality costant K

The situation is more complex: ionization quenching

- If dE/dx is low → density of excited molecules is small→ interaction between them is negligible → more light
- If dE/dx large→ density of excited molecules is high → interaction between them leads to non radiative de-excitation → less light

Quenching has two consequences:

- The relation between E and N_{pe} is no more linear
- The number of N_{pe} depends on the particle nature (β, α, γ..)

Number of collected photons→ Energy reco

Ionization Quenching

Birks law

$$\frac{dL}{dx} = \frac{S\,\frac{dE}{dx}}{1 + kB\,\frac{dE}{dx}}$$

Density of excited/damaged molecules

- Birks empirical parametrization of quenching;
- There are also other parametrizations

- For electrons with E> ~150 keV dE/dx is small → dL/dx=SdE/dx → L=SE
- For p, alfas, dE/dX is large → dL/dX→ dL/dx ~S/kB
- **EXAMPLE**: the scintillator light produced by alfas (~5 MeV), is approximately 1/10 of the light produced by an electron of the same energy

Number of collected photons→ Energy reco

The addition of Cerenkov photons

- Charged particles travelling in a medium with a velocity greater than the velocity of light in that medium produce Cerenkov light;
- This happens also in the scintillation media, of course;
- Typically, an electron must have a kinetic energy > 200 keV to emit Cerenkov light;
- Cerenkov light is a small portion of the scintillation light (<1%), but Cerenkov photons add to the total amount of photons emitted by the scintillator;
- Since it is a threshold effect, it introduces extra non-linearity in the scintillation energy response;

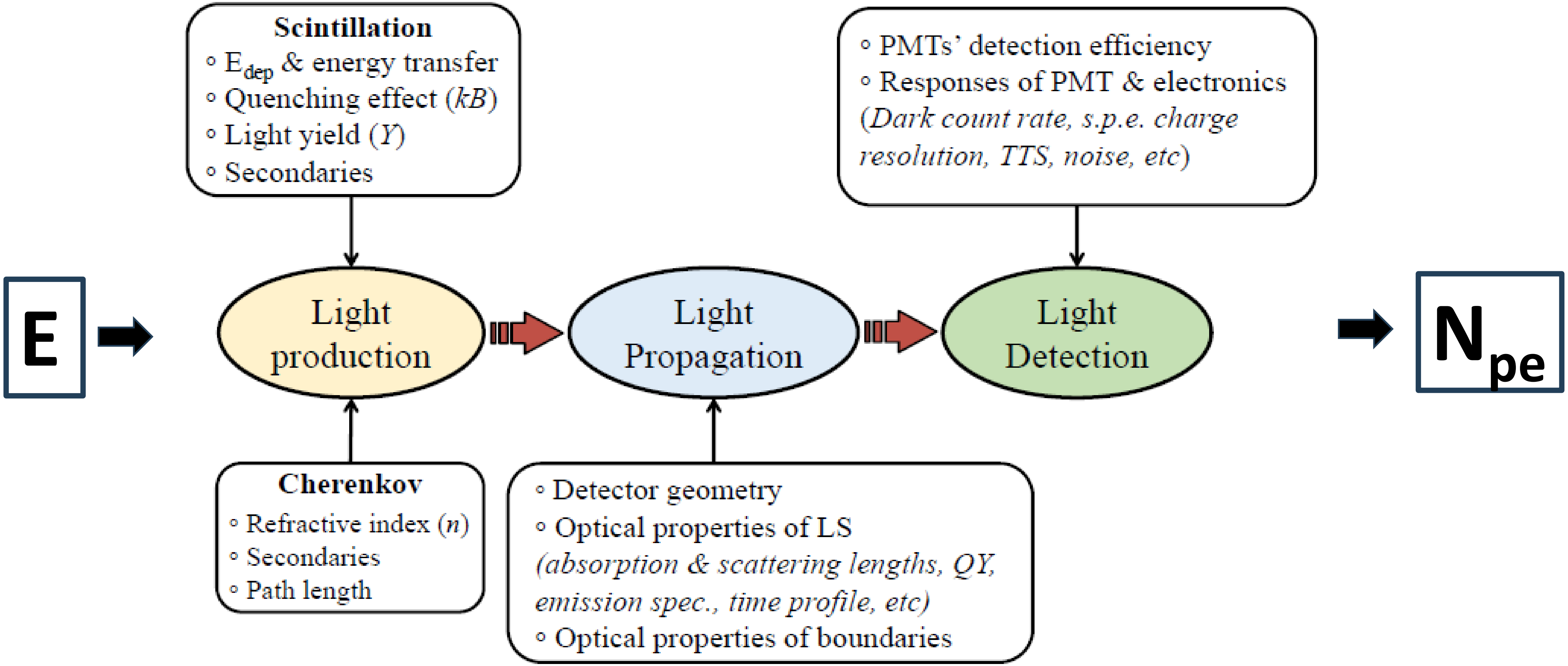
Number of collected photons→ Energy reco

$$\boxed{E} \rightarrow \boxed{N_{pe}}$$

Number of collected photons→ Energy reco

$$\boxed{E} \rightarrow \boxed{?} \rightarrow \boxed{N_{pe}}$$

Number of collected photons→ Energy reco



E →

Scintillation
- E_{dep} & energy transfer
- Quenching effect (kB)
- Light yield (Y)
- Secondaries

Cherenkov
- Refractive index (n)
- Secondaries
- Path length

Light production ⇒ Light Propagation ⇒ Light Detection

- Detector geometry
- Optical properties of LS *(absorption & scattering lengths, QY, emission spec., time profile, etc)*
- Optical properties of boundaries

- PMTs' detection efficiency
- Responses of PMT & electronics *(Dark count rate, s.p.e. charge resolution, TTS, noise, etc)*

→ N_{pe}

Number of collected photons→ Energy reco

E →

Simulations

- Need to know all parameters: LY, emission spectrum, amount of Cherenkov, L_{ass} probability of re-emission after absorption, QE..
- These parameters may be studied in laboratory;
- Impossible to determine them with sufficient precision:
  - Size of the detectors are huge
  - Strong correlation between parameters

→ **N_{pe}**

Number of collected photons→ Energy reco

E →

Calibrations

- Calibrations are fundamental to determine the correspondencebetween E→ Npe for
    - Different Energies,
    - Different particle types,
    - Different positions in the real detector
- This is crucial to fine-tune the Montecarlo input parameters ;
- Calibrations should be repeated periodically, also to cross-check possible variations in time

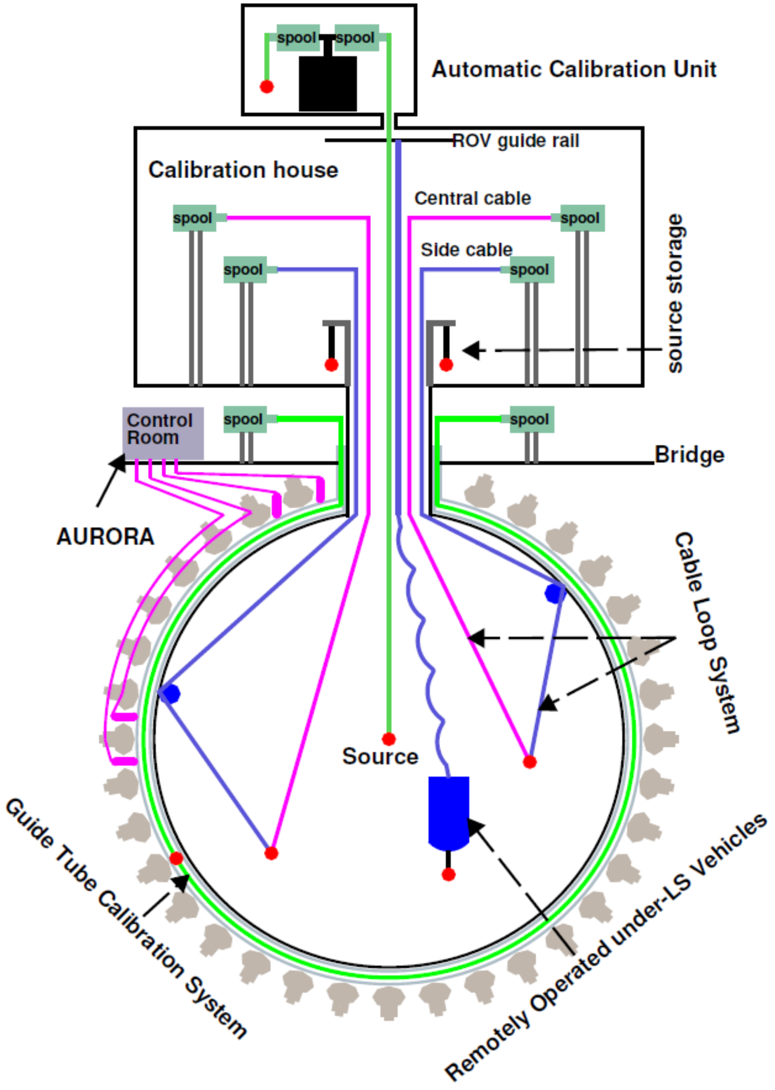
→ N_{pe}

Calibrations

Example 1: The calibrations in JUNO

Systems to deploy sources in different positions

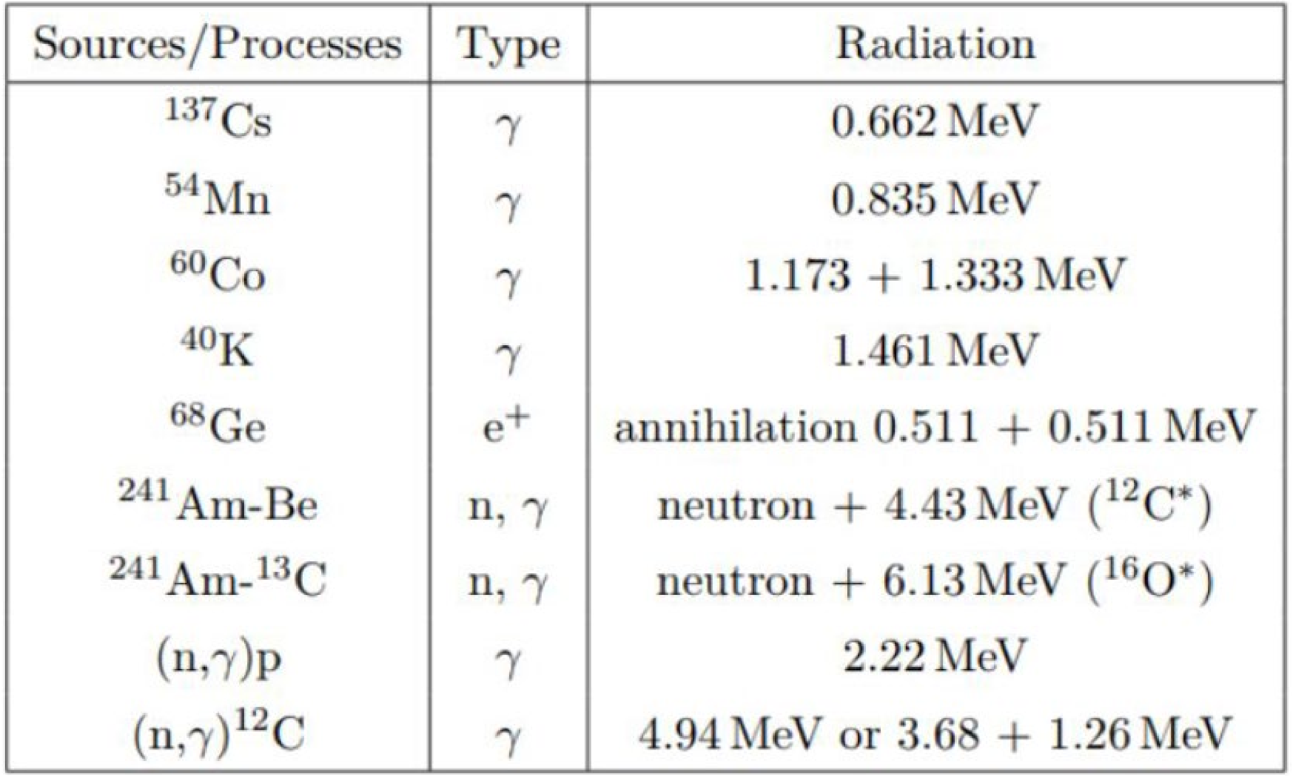
- ACU (Automatic Calibration Unit) : central axis
- CLS (Cable Loop System): out of axis on a plane
- ROV (Remotely Operated Vehicle): in the full volume



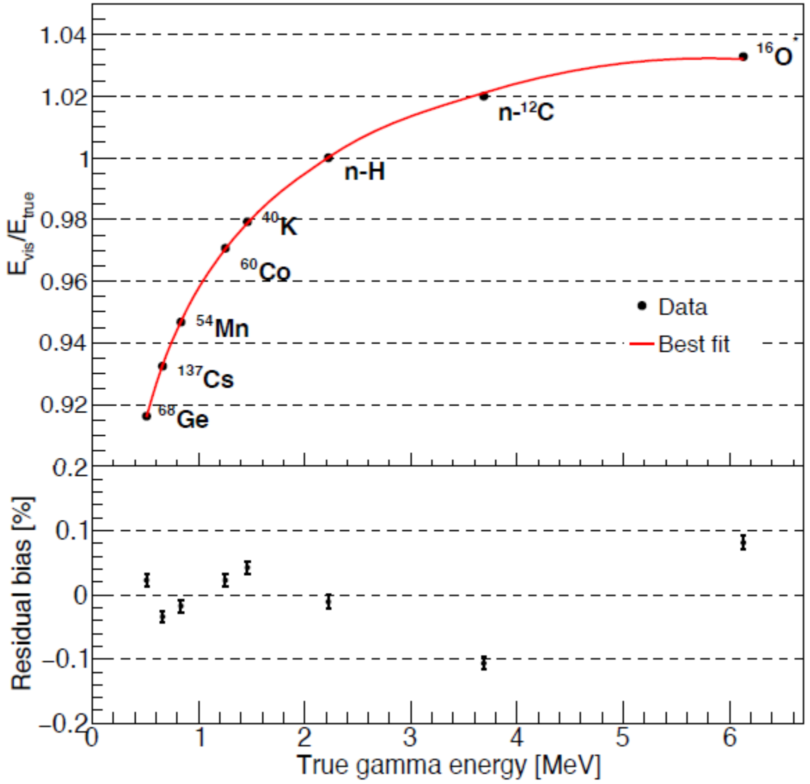
Calibrations

Example 1: The calibrations in JUNO (and Borexino)

Sources at different energies in the energy range of interest to characterize the non-linearity



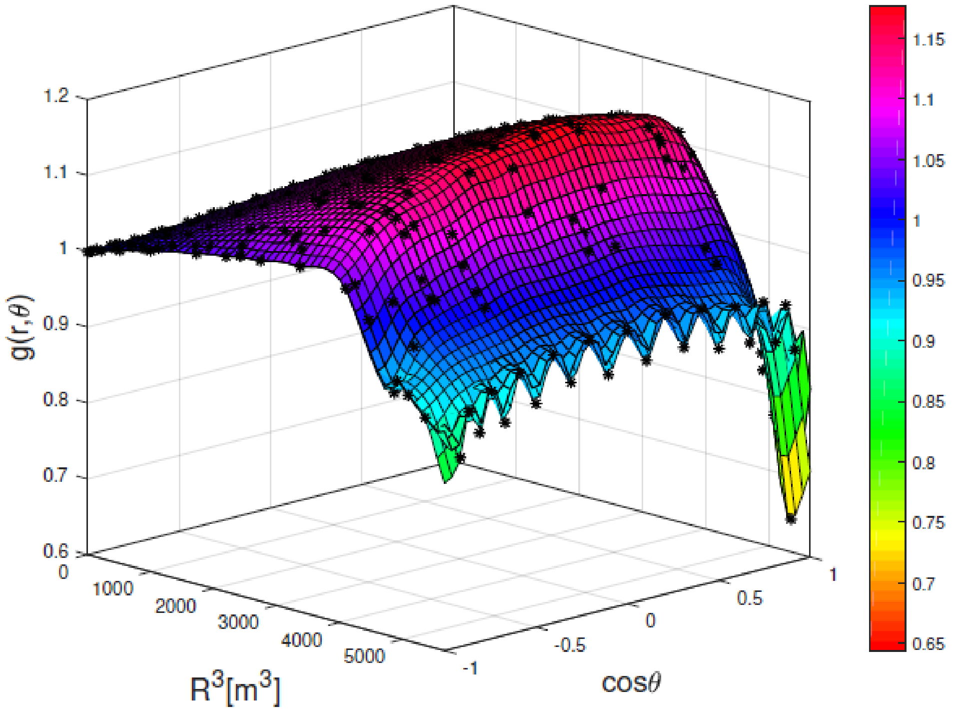
Sources/Processes	Type	Radiation
^{137}Cs	γ	0.662 MeV
^{54}Mn	γ	0.835 MeV
^{60}Co	γ	1.173 + 1.333 MeV
^{40}K	γ	1.461 MeV
^{68}Ge	e^+	annihilation 0.511 + 0.511 MeV
^{241}Am-Be	n, γ	neutron + 4.43 MeV (^{12}C*)
^{241}Am-^{13}C	n, γ	neutron + 6.13 MeV (^{16}O*)
(n,γ)p	γ	2.22 MeV
(n,γ)^{12}C	γ	4.94 MeV or 3.68 + 1.26 MeV



Calibrations

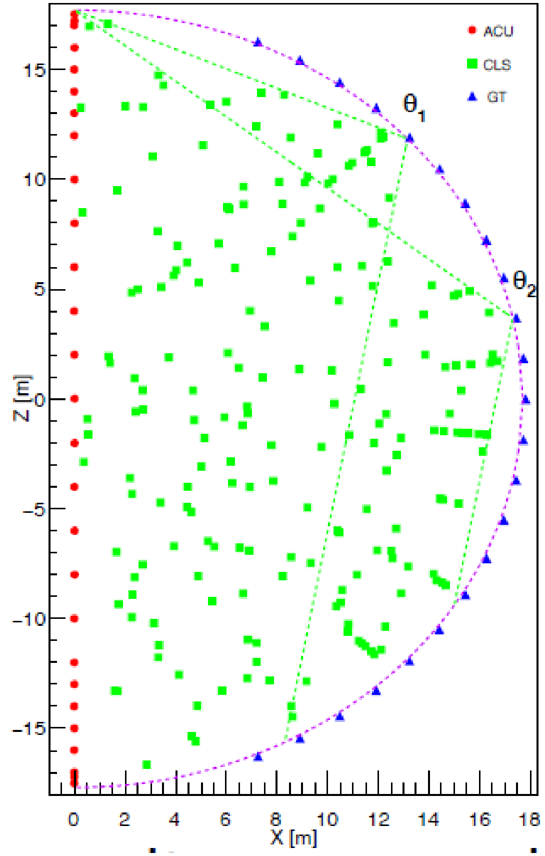
Example 1: The calibrations in JUNO (and Borexino)

Sources in 250 points in the scintillator volume to characterize the non-uniformity



Variations as large as 10% on Npe in the scintillator volume due to light propagation effects;

Must be corrected to avoid loss of energy resolution



Calibrations

Example 2: monitoring the scintillator transparency

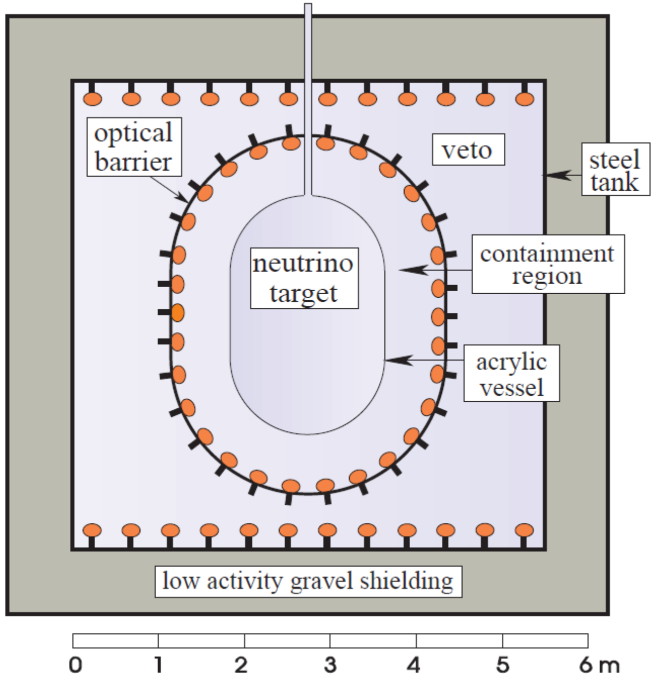
- The transparency is a critical issue especially in large detectors, since it is directly related to the number of collected photons;
- What if it changes (reduces) in time?

- For example, the CHOOZ detector (1996's) used a Gd-loaded scintillator to increase the neutron capture probability in the IBD reaction

$$\overline{\nu}_e + p \rightarrow e^+ + n \quad (\text{IBD})$$

- After 4 months of operation, in 1997 they needed to replace the scintillator, because it had become ''yellowish'';
- This was due to chemical instability;

CHOOZ Detector



Calibrations

Example 2: monitoring the scintillator transparency in SNO+

The ELLIE (Embedded LED/Laser Light Injection Entity) system in SNO+

Timing ELLIE:

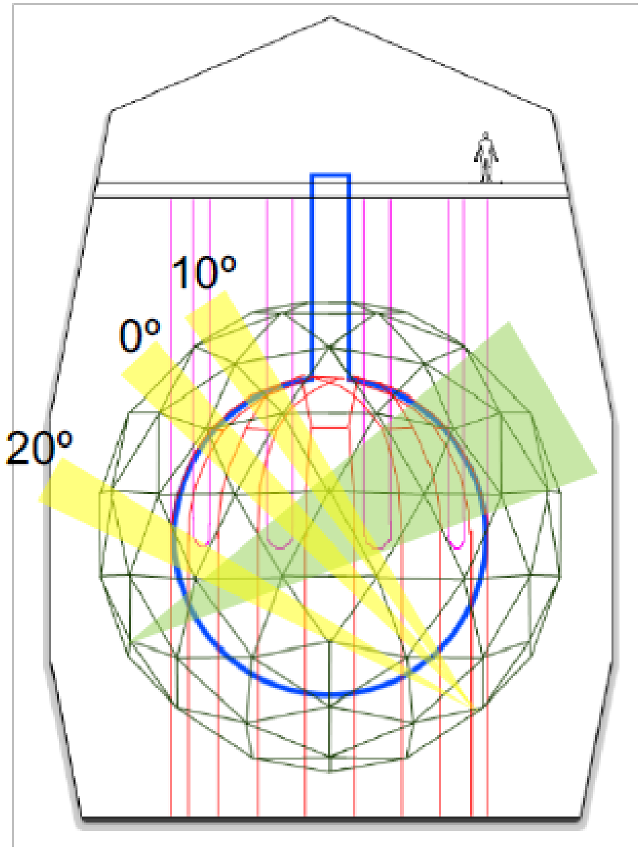
- 91 injection points
- LEDs @ 435n (non collimated beam)

Attenuation Monitoring for Ellie

- 8 injection points
- LEDs @ 385nm and 500 nm

Scattering Monitoring for ELLIE:

- 12 injection points
- Laser @ several l (375nm, 405nm, 445nm, 495nm..) (collimated beam)



Calibrations

Example 3: monitoring the scintillator transparency in Borexino

Radial system: shooting light radially

→ go through the scintillator

→ study transparency of the scintillator at 394 nm);

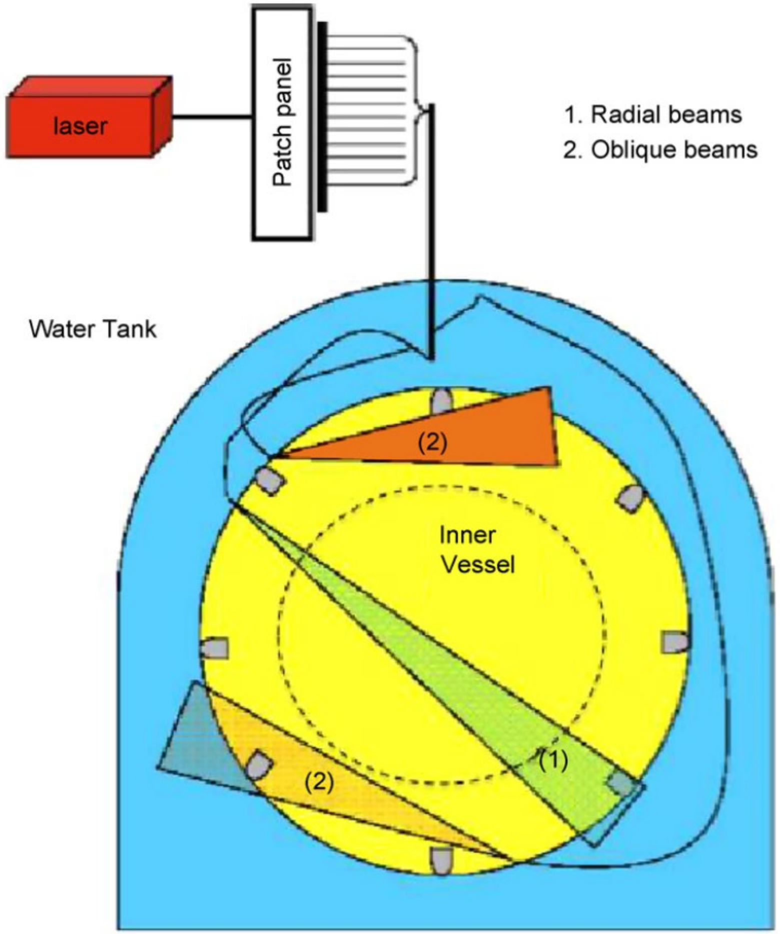
Oblique system: shooting light at an angle

→ go only through the buffer

→ study scattering at 394 nm and 355 nm;

→ Light crosses different lengths (from 2.5m to 8 m)

Beams are collimated (opening angle between 2° and 6°



Energy reconstruction: why we need it?

The importance of reconstructing ENERGY

Example 1: determining the neutrino mass ordering with JUNO

- JUNO will detect anti-ν from power plans located 53 Km away;
- Anti-nu can undergo oscillations in their path from the reactors to JUNO;

Energy reconstruction: why we need it?

The importance of reconstructing ENERGY

Example 1: determining the neutrino mass ordering with JUNO

- JUNO will detect anti-ν from power plans located 53 Km away;
- Anti-nu can undergo oscillations in their path from the reactors to JUNO;

$\bar{\nu}_e$ survival probability: $\boldsymbol{P_{ee} = 1 - P_{21} - P_{31} - P_{32}}$

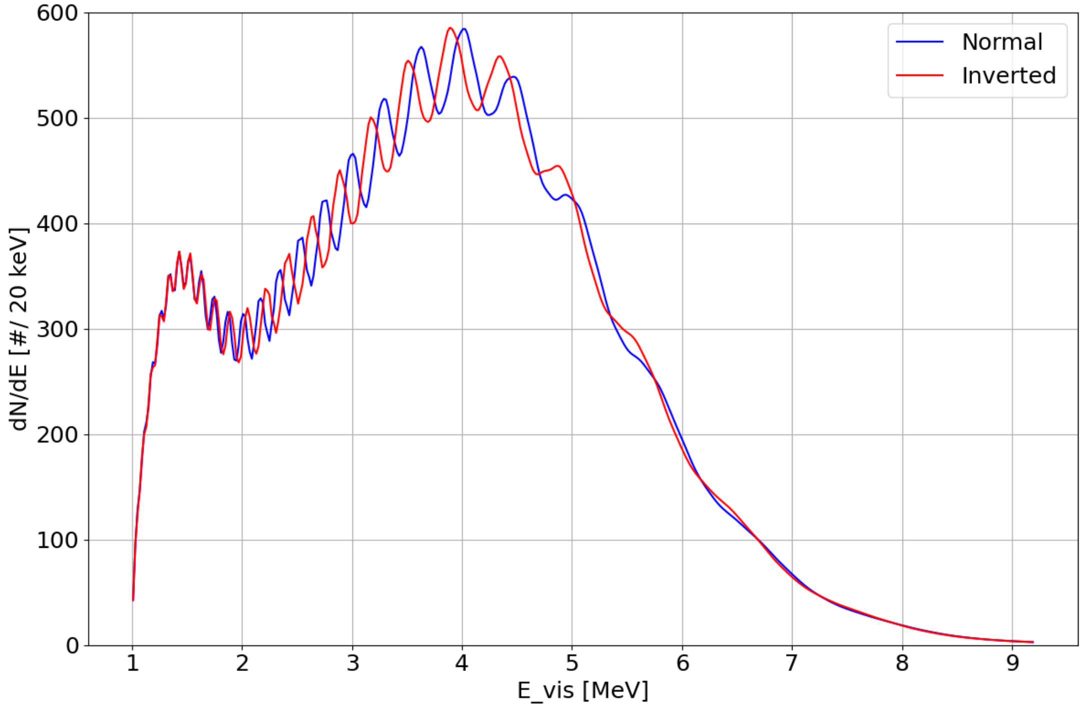
$$P_{21} = \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

$$P_{31} = \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{31}$$

$$P_{32} = \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{32}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

- It depends on the ν mass ordering!



To distinguish between the two cases we need good energy resolution (~3% @1MeV)!

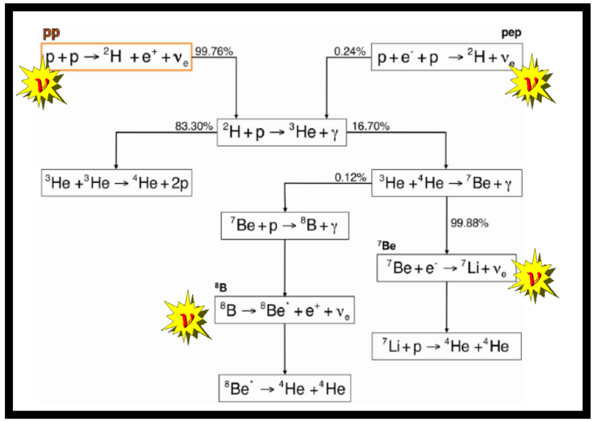
Energy reconstruction: why we need it?

The importance of reconstructing ENERGY

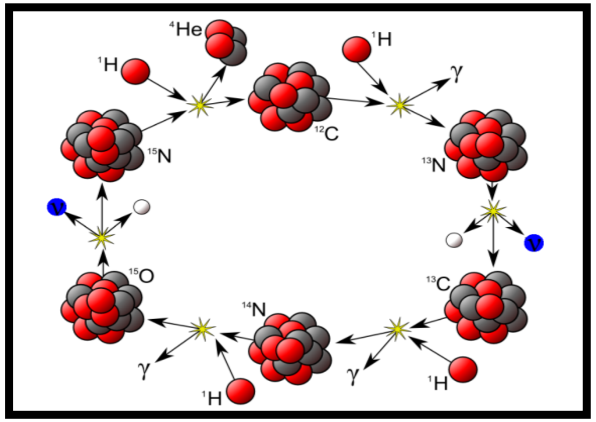
Example 2: spectroscopy of solar neutrinos (Borexino)

- The Sun emits ν_e from different nuclear reactions occurring in its core;
- Neutrinos from different reactions have different energies;

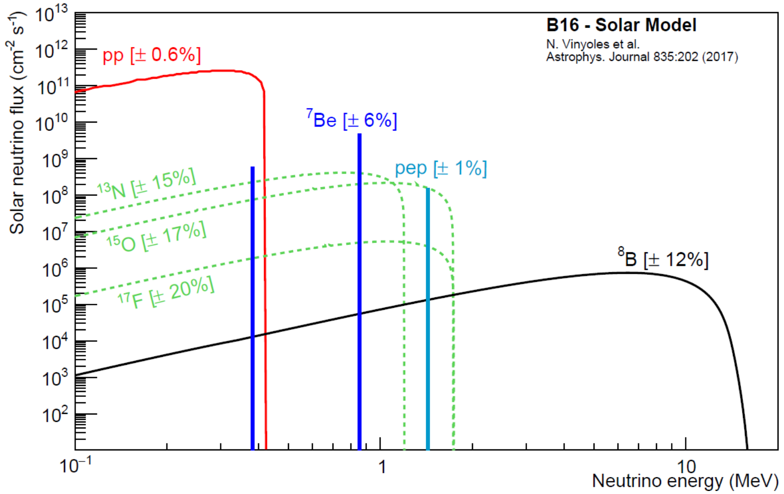
p-p chain (99%)



CNO cycle (1%)



Energy distribution of solar neutrinos



➢ **These differences allow to measure the neutrino flux from each reactions separately**

Energy reconstruction: why we need it?

The importance of reconstructing ENERGY

Example 2: spectroscopy of solar neutrinos (Borexino)

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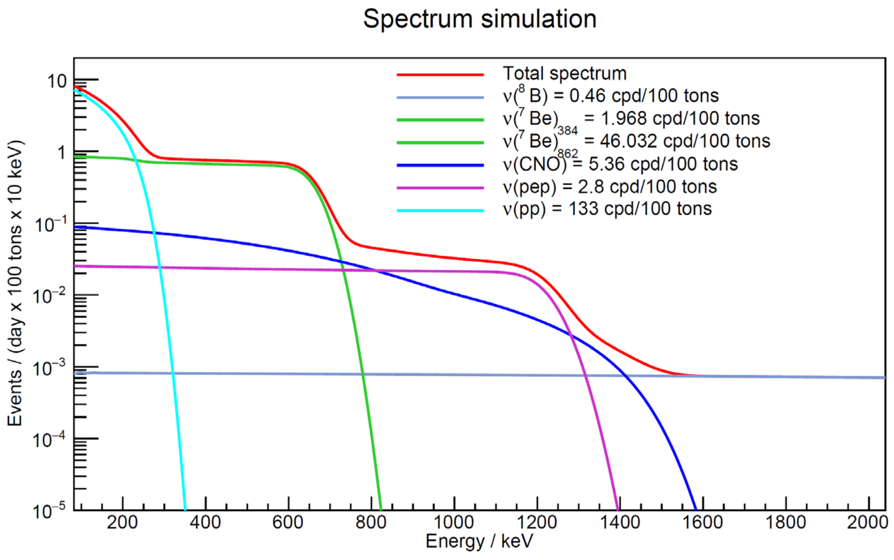
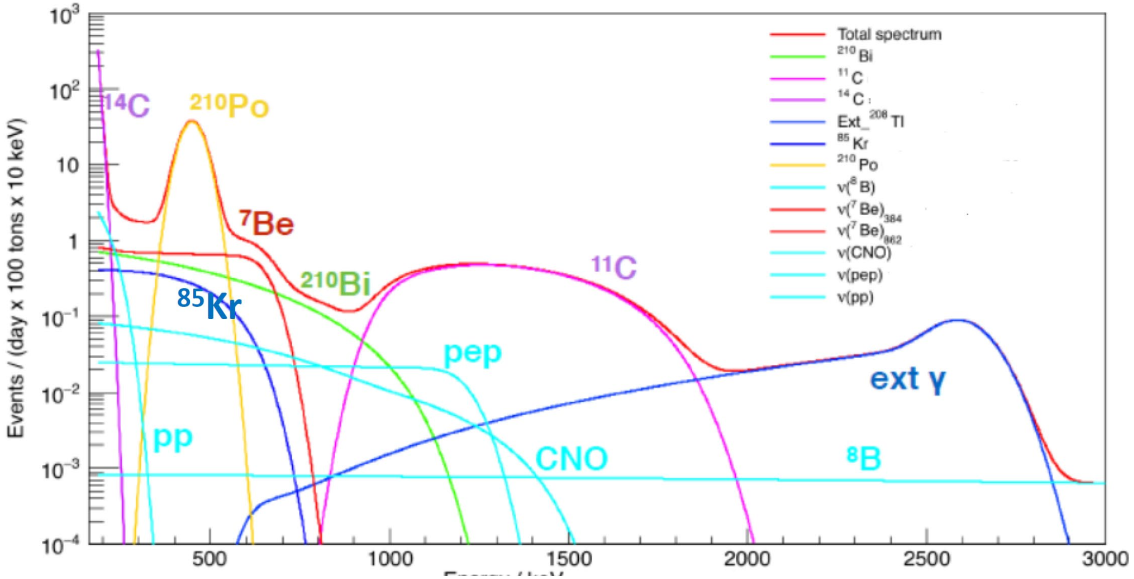
- Neutrinos from different reactions have different energies;





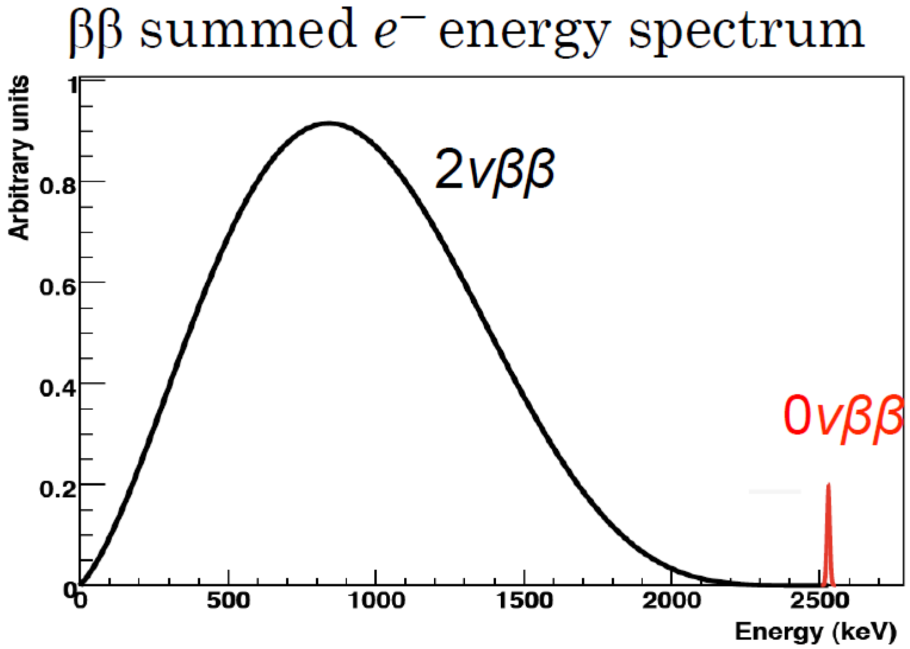
➢ **Energy reco is also crucial to separate signal from backgrounds!**

Energy reconstruction: why we need it?

The importance of reconstructing ENERGY

Example 3: Neutrinoless Double Beta Decay (SNO+ and KamLAND-Zen)

- Neutrinoless Double Beta Decay shows up as a peak in the energy distribution of events at the Q-value of the reaction
- The better the resolution, the narrower the peak is → less events from backgrounds



Scintillators have not optimal resolution

BUT

They can reach very high radiopurity!

- The 2 Neutrino Double Beta Decay ($2\nu-\beta\beta$ decay) is an irreducible background;
- ^{136}Xe and ^{130}Te have been chosen also because $T_{1/2}$ ($2\nu-\beta\beta$) is high (~ 10^{21} years)

Info for each event

Number of collected photons → **Energy**

$$\frac{\sigma(E)}{E} \sim \frac{3-5\ \%}{\sqrt{E}}$$

Time of arrival of collected photons @ each PMT → **Position**

$$\frac{\sigma(x)}{x} \sim \frac{10\text{–}20\ \text{cm}}{\sqrt{E}}$$

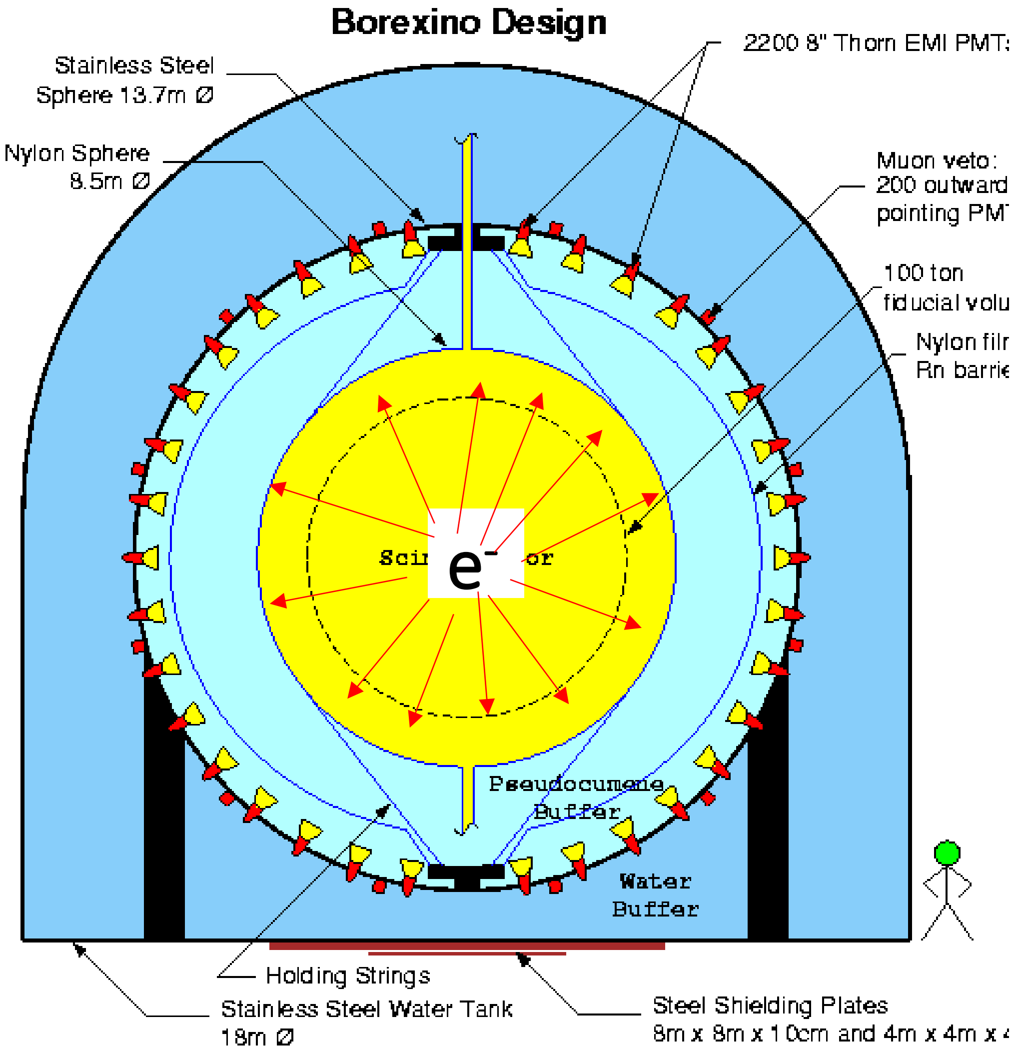
Time of arrival of collected photons @ each PMT → **Pulse-shape discrimination**

$$\alpha,\ \beta^-,\ \beta^+$$

Position reconstruction

Time of collected photons→ position reco

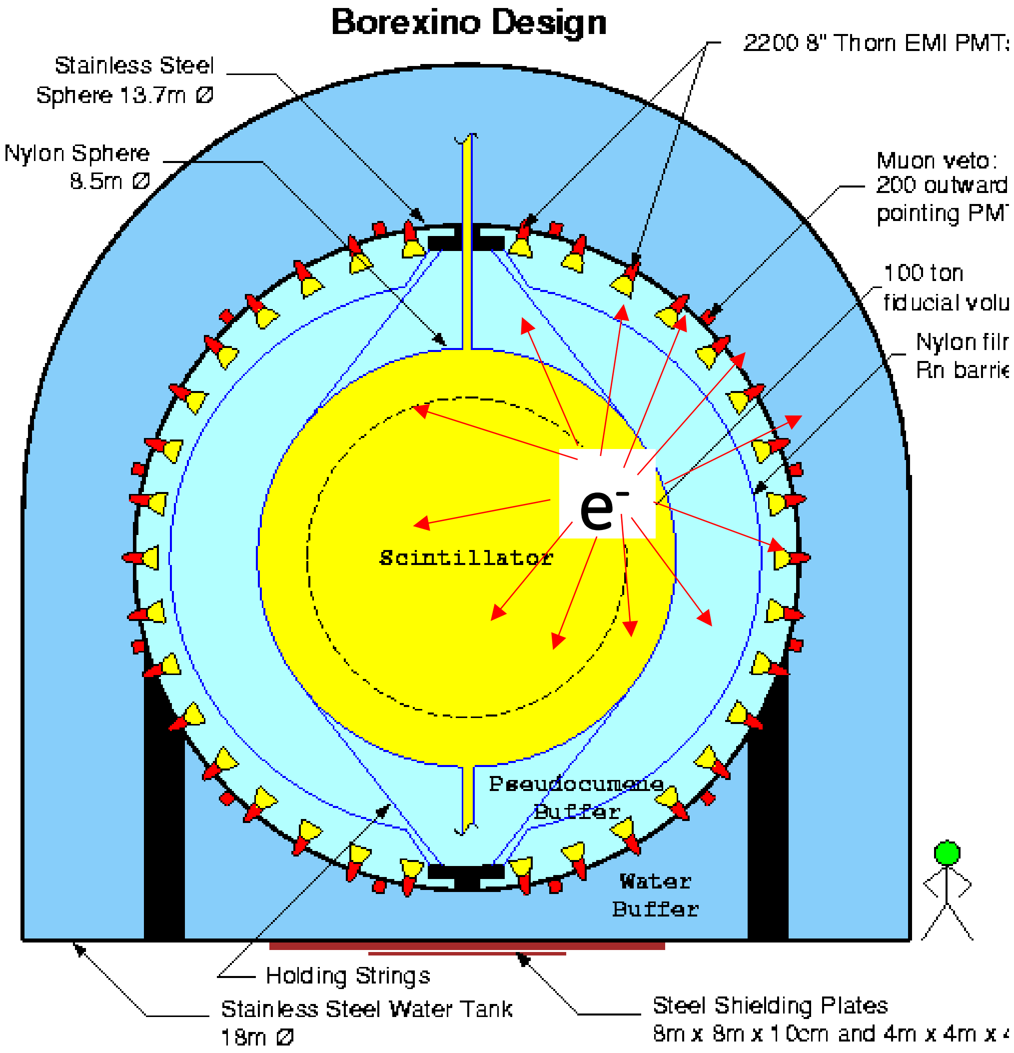
- The position of the neutrino interaction can be determined by the arrival times of the detected photons;
- For an event in the center, photons arrive ~ at the same time;



Time of collected photons→ position reco

- The position of the neutrino interaction can be determined by the arrival times of the detected photons;
- For an event in the center, photons arrive ~ at the same time;
- For an event out of the center the PMTs closer to the interaction point will arrive first;
- PROBLEM: the scintillator photons emission time is not instantaneous;

This must be taken into account for proper position reconstruction



Time of collected photons→ position reco

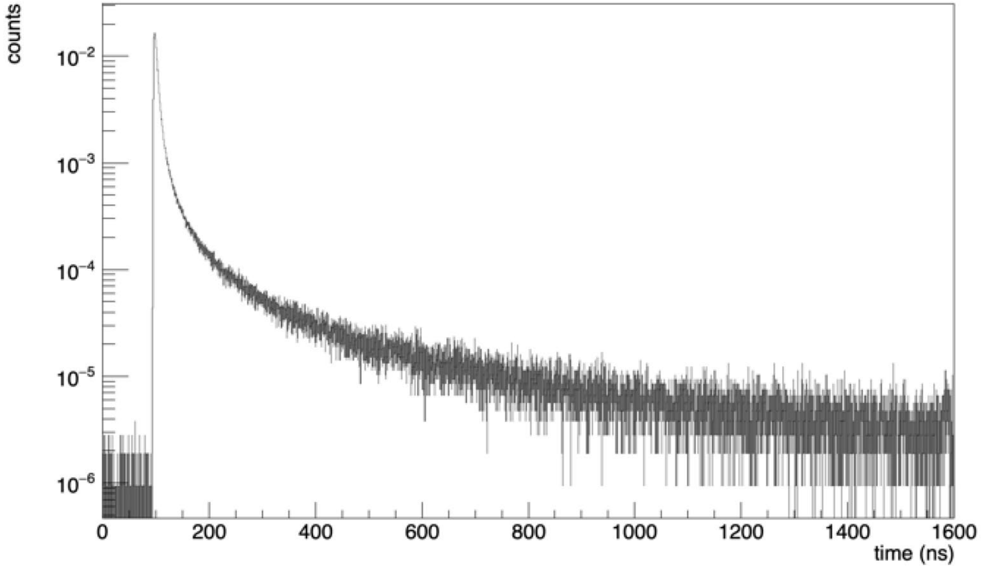
The scintillation light is not emitted istantaneously

- Fast component: fluorescence of the solute
- Other components: delayed fluorescence

- The time distributions of emitted photons can be described by a multi-exponential decay;

$$\sum_{i=1}^{4} \frac{q_i}{\tau_i} e^{-\frac{t}{\tau_i}}$$

τ_1 ~ ns (fluorescence)
$\tau_2 < \tau_3 < \tau_4 < \tau_N$ (delayed fluorescence)
$\tau_2\ \tau_3\ \tau_4$ from ~tens ns → to μs



- The fast component is dominant (>~80%) → organic liquid scintillators are fast (compared to the typical time of flight of photons)!

➢ Position reconstruction is feasible

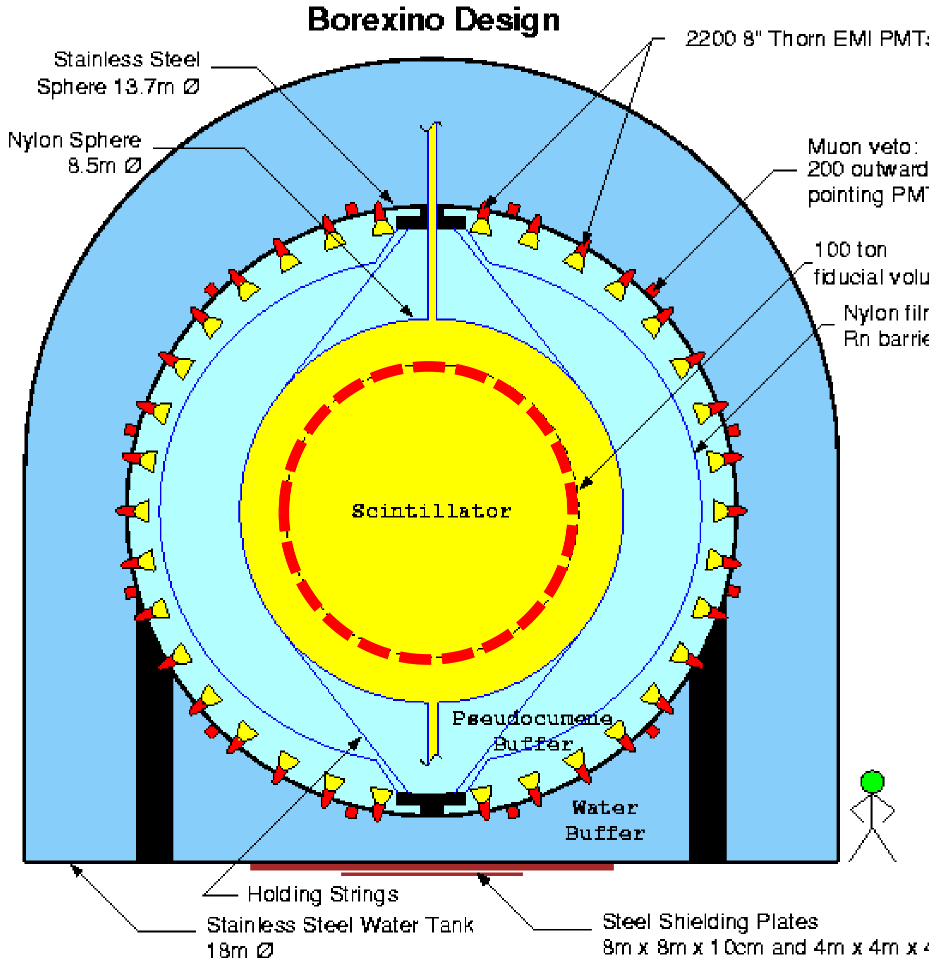
Position reconstruction: why we need it?

The importance of reconstructing POSITION

Example 1: reduction of external background

- The onion-like structure of most liquid scintillator detectors (for example Borexino) protects the core from external radioactivity;
- However, this may not be enough:
    - Gammas from PMTs may cross the 2m thick buffer and reach the vessel;
    - Radioactivity from the vessel surface enters in the scintillator;

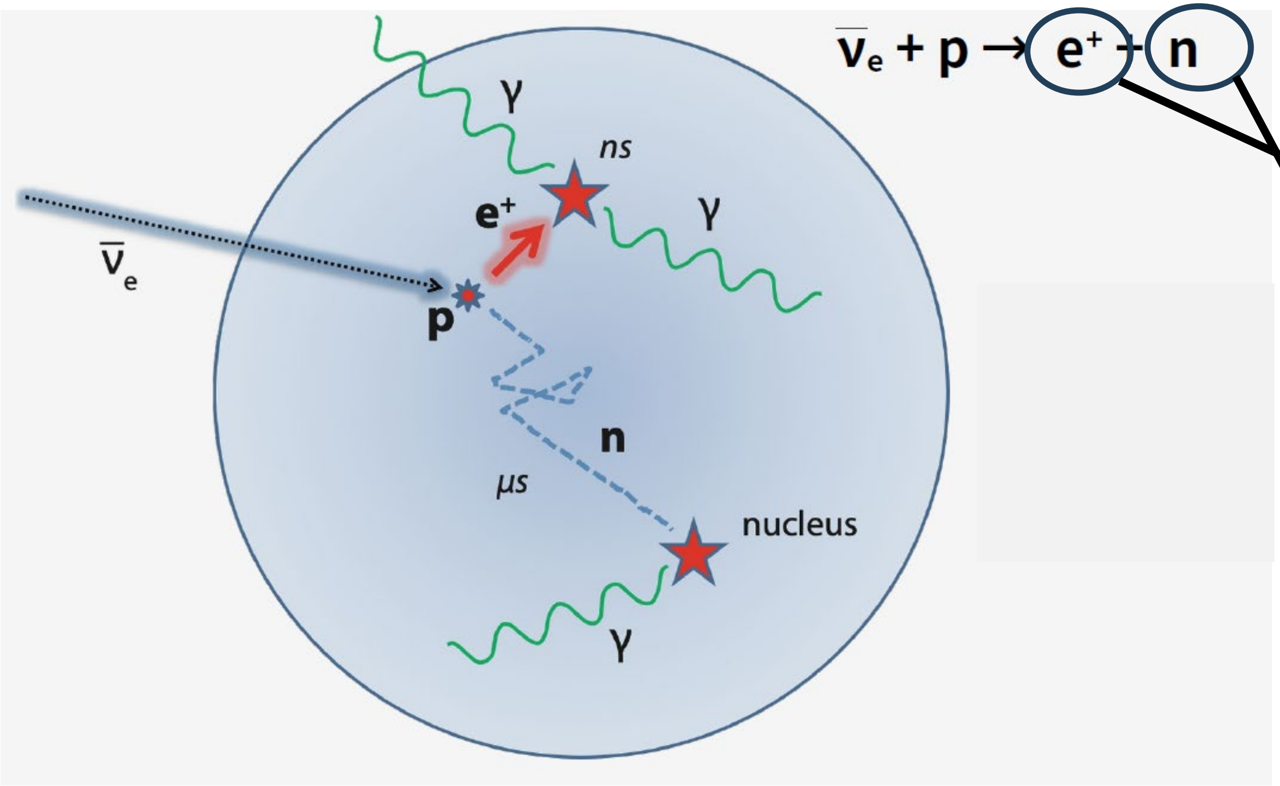
Select only events with the position in an inner region of the scintillator (Fiducial Volume)



Position reconstruction: why we need it?

The importance of reconstructing POSITION

Example 2: IBD event selection in JUNO



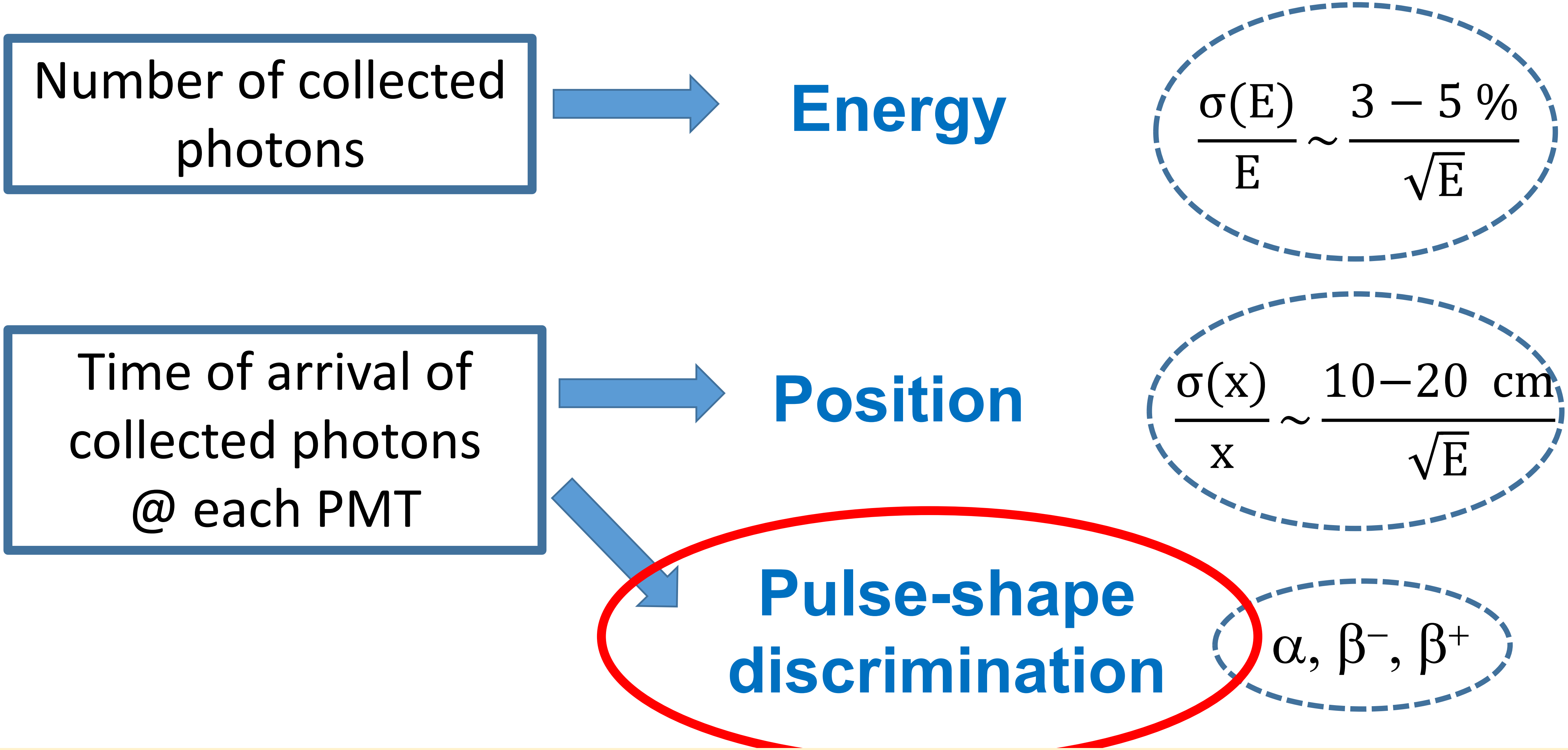
When neutrino interacts via the IBD reaction, it produces two events in sequence

Prompt event: e^+ which annihilates producing 2 γ

Delayed event : after ~ 200 μs, the neutron is captured emitting 2.2 MeV γ

Asking that these two consecutive events are close in position, removes a lot of accidental background

Info for each event



Number of collected photons

Energy

$$\frac{\sigma(E)}{E} \sim \frac{3-5\ \%}{\sqrt{E}}$$

Time of arrival of collected photons @ each PMT

Position

$$\frac{\sigma(x)}{x} \sim \frac{10-20\ \text{cm}}{\sqrt{E}}$$

Pulse-shape discrimination

α, β^-, β^+

Alfa/beta discrimination

The INFN School on Underground Physics

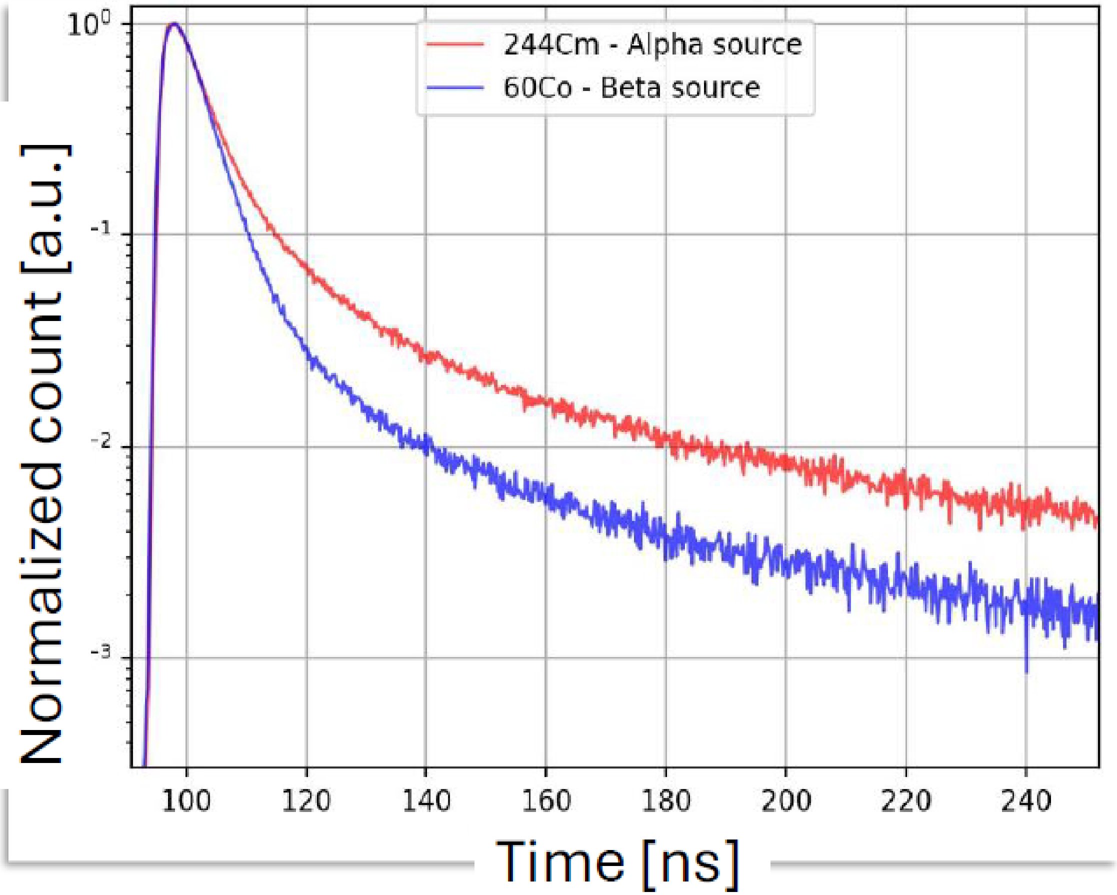
Time of collected photons→ particle discrimination

The INFN School on Underground Physics

Emission times of the liquid scintillator light and particle discrimination

- The time distribution of emitted photons depends on the nature of the ionizing particle;
- Alfa particles have a longer tail with respect to beta particles;
- In fact larger dE/dx -→ larger density of molecules excited in the T state → delayed fluorescence is larger

Very useful tool for particle discrimination!



Time of collected photons→ particle discrimination

- A lot of the isotopes belonging to the U and Th chain decay emitting an alfa particle;
- It is possible to evaluate the probability that an event is α or β exploiting time distribution

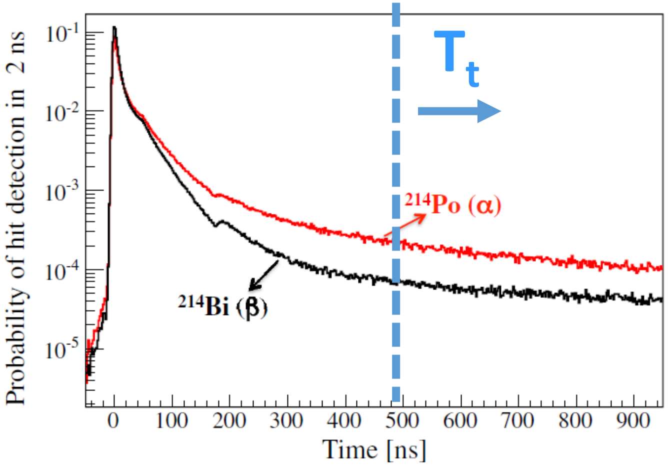
Simple method: the tail-to-tot ratio

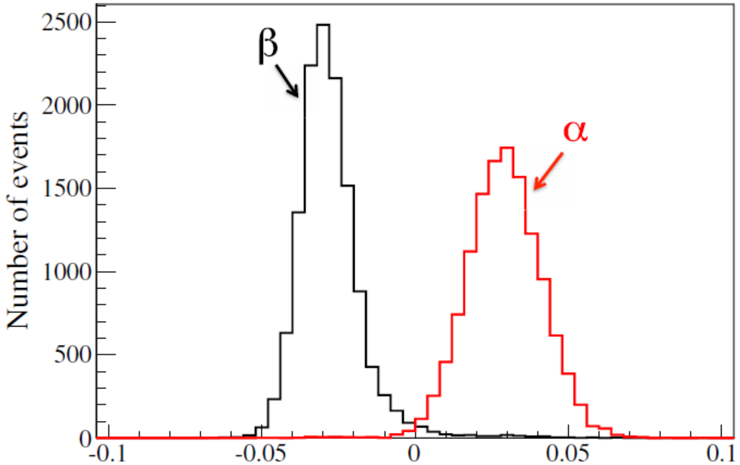
Evaluating the ratio R= N(photon for $t>T_t$)/N(tot)

R(alfa) > R(beta)

More complex methods (Neural Network or similar…) can have better efficiency in separating alpha/beta

The method must be trained on samples of α's or β's





Particle discrimination: why do we need it?

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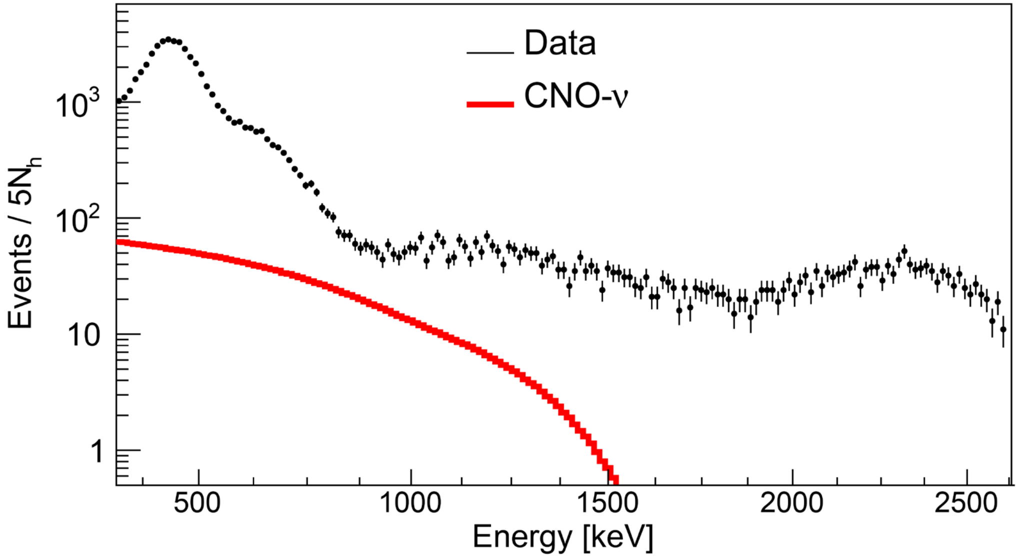
Example 1: the 210Po "saga" in Borexino and solar neutrinos from CNO cycle

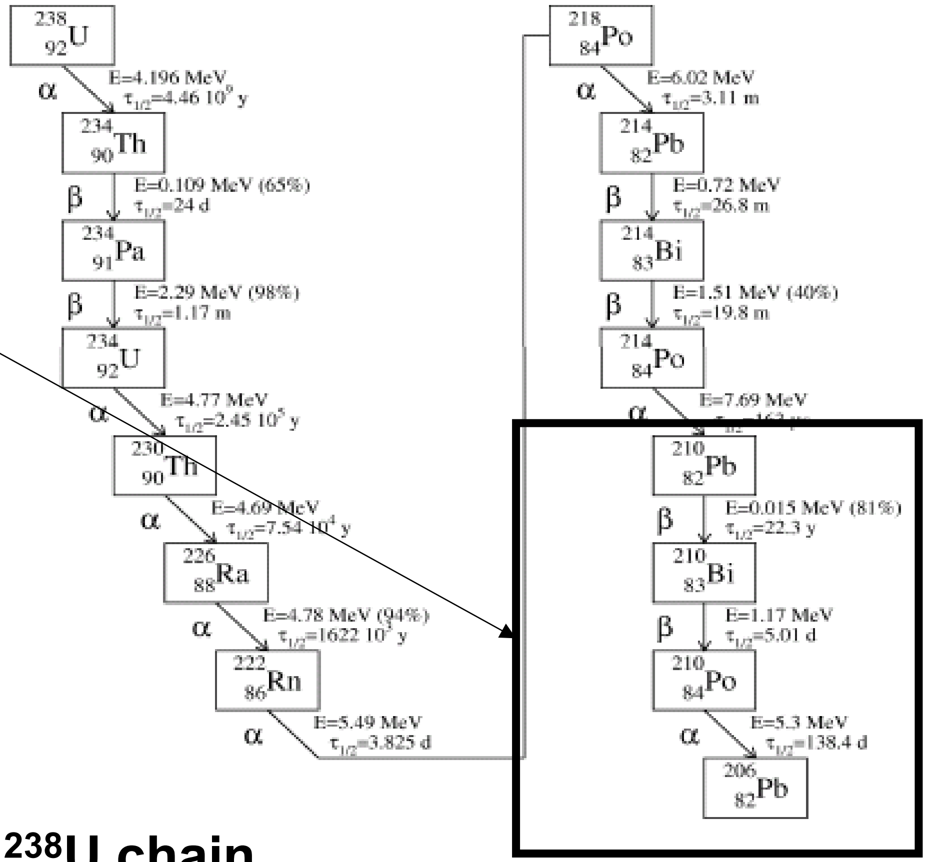
$^{210}\text{Pb} \rightarrow {}^{210}\text{Bi} + \beta^- \ (\tau=33\text{y})$

$^{210}\text{Bi} \rightarrow {}^{210}\text{Po} + \beta^- \ (\tau=7\text{d})$

$^{210}\text{Po} \rightarrow {}^{206}\text{Pb} + \alpha \ (\tau=200\text{d})$

^{210}Bi is the most annoying background for the CNO neutrino search





^{238}U chain

Particle discrimination: why do we need it?

Example 1: the 210Po ''saga'' in Borexino and solar neutrinos from CNO cycle

^{210}Pb → ^{210}Bi + β^- (τ=33y)
^{210}Bi → ^{210}Po +β^- (τ=7d)
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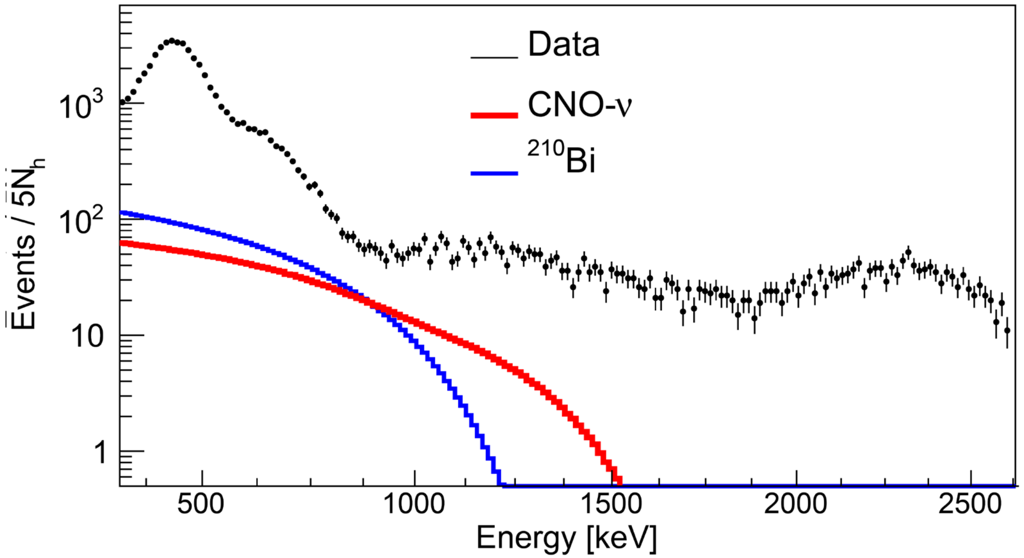
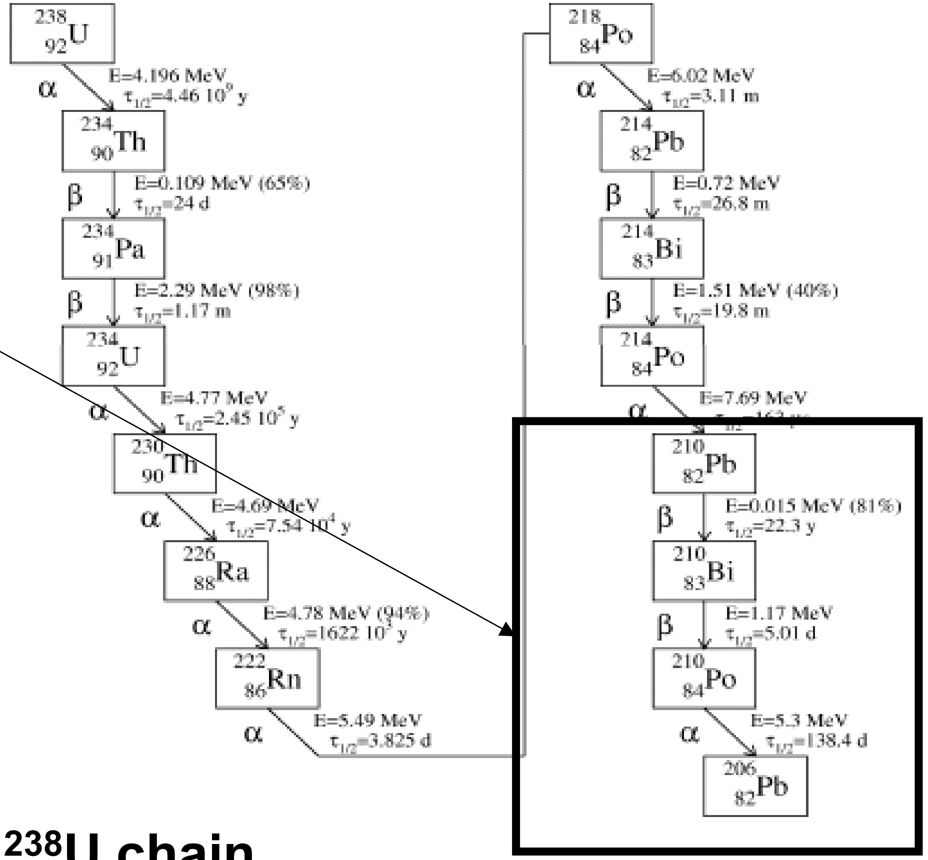
^{210}Bi is the most annoying background for the CNO neutrino search





^{238}U chain

Particle discrimination: why do we need it?

Example 1: the 210Po "saga" in Borexino and solar neutrinos from CNO cycle

$^{210}Pb \rightarrow {}^{210}Bi + \beta^- \ (\tau=33y)$

$^{210}Bi \rightarrow {}^{210}Po + \beta^- \ (\tau=7d)$

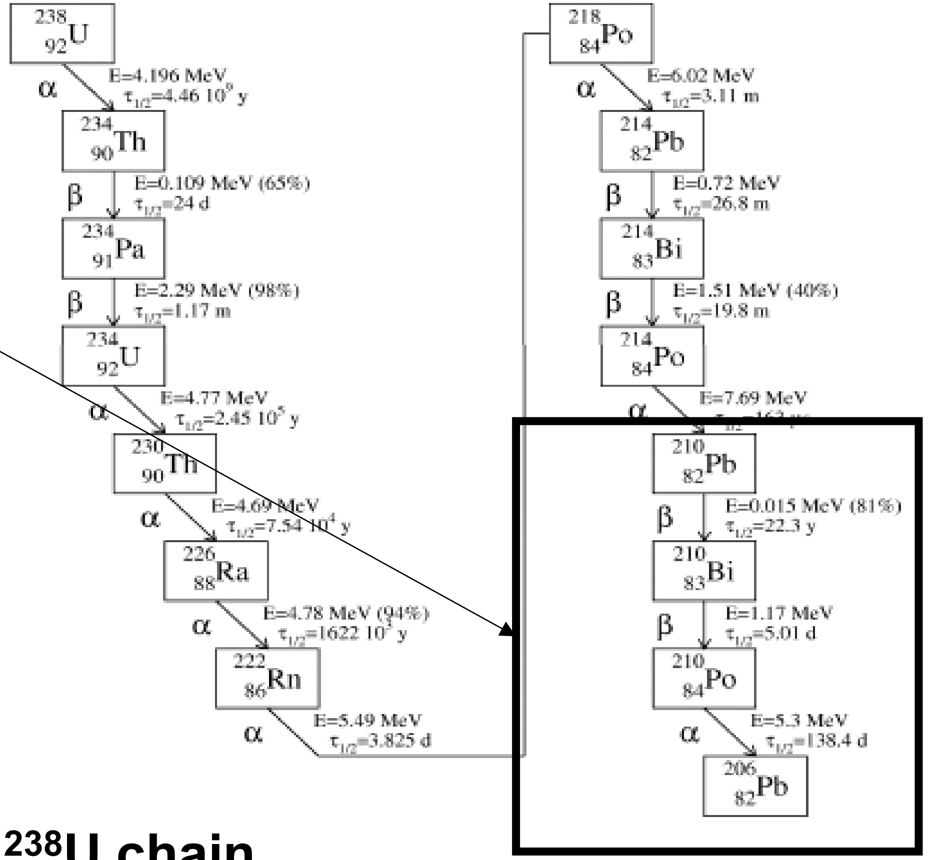
$^{210}Po \rightarrow {}^{206}Pb + \alpha \ (\tau=200d)$

^{210}Bi is the most annoying background for the CNO neutrino search

At secular equilibrium, rate(^{210}Po) = rate(^{210}Bi);

^{210}Po decays alfa →it can be easily recognized and tagged by pulse-shape discrimination

From the rate of ^{210}Po →^{210}Bi can be determined and subtracted to isolate the signal from CNO neutrinos



^{238}U chain

Particle discrimination: why do we need it?

Example 1: the 210Po "saga" in Borexino and solar neutrinos from CNO cycle

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^{210}Po → ^{206}Pb +α (τ=200d)

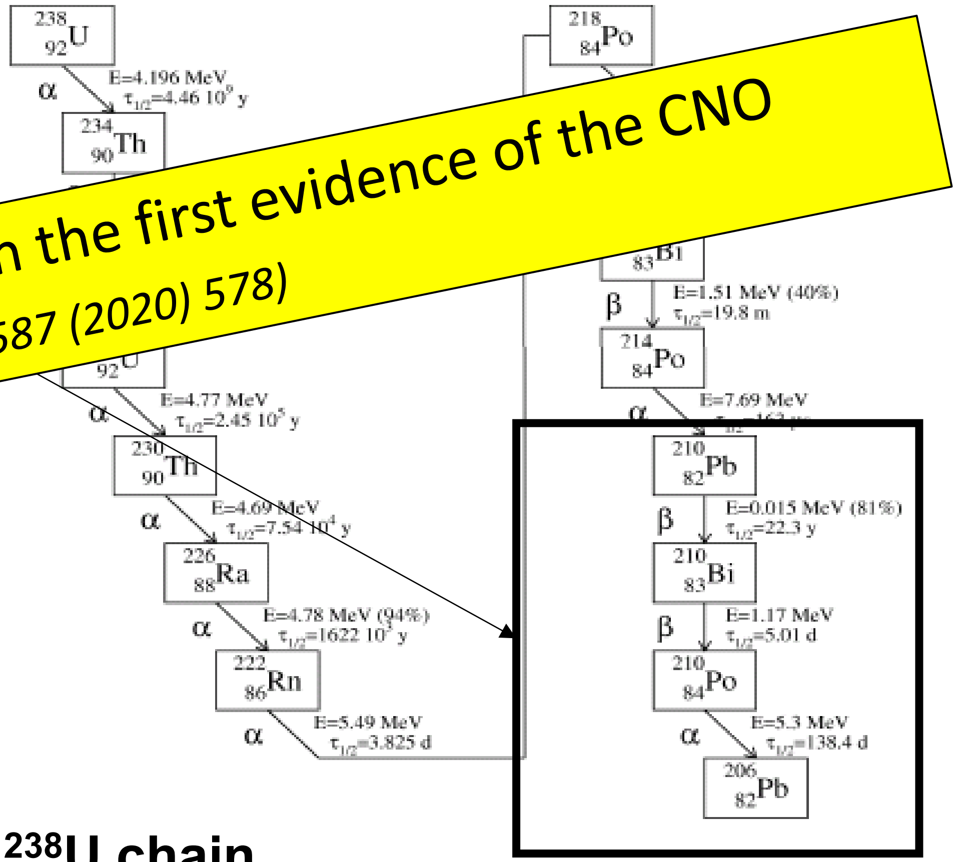
^{210}Bi is the most annoying backgroun
CNO neutrino search

At **e(^{210}Bi);**

2 nd →it can be easily recognized and tagged by pulse-shape discrimination

Thanks to the ^{210}Bi tagging via ^{210}Po, Borexino has given the first evidence of the CNO cycle in the Sun with a 5σ significance in 2020 (*Nature 587 (2020) 578)*

From the rate of ^{210}Po →^{210}Bi can be determined and subtracted to isolate the signal from CNO neutrinos



^{238}U chain

Requirements for underground experiments

RARE EVENTS

- Large Masses
- Long data-taking (stability in time)

Background Control

- Underground facilities
- Shielding Strategy
- Veto system
- Radiopurity

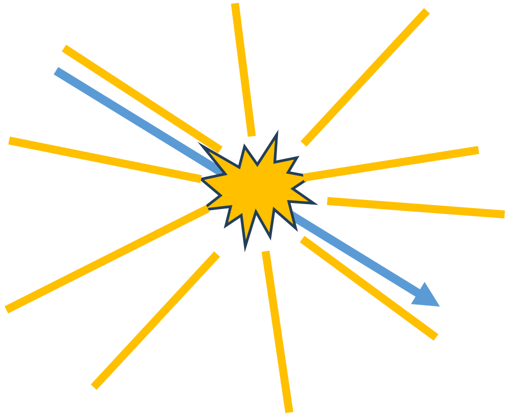
Info for each event

- Count signal events
- Measure energy
- Measure position of interaction
- Measure direction

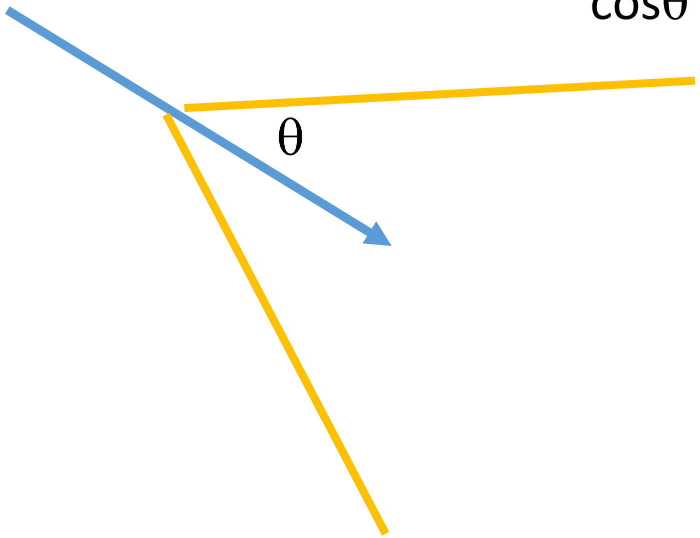
Reconstructing direction with liquid scintillators

Scintillation light is emitted isotropically → information regarding the particle direction is lost

Scintillation



Cerenkov



The particle must travel faster than the speed of light in the medium

In principle, un-segmented scintillator detector devoted to solar and reactor neutrinos **cannot** measure the direction of the incoming particle (..unless they get some help from Cerenkov..)

A short detour... Cerenkov detectors

(See more in the following lesson…)

Reconstructing direction in Cerenkov detectors

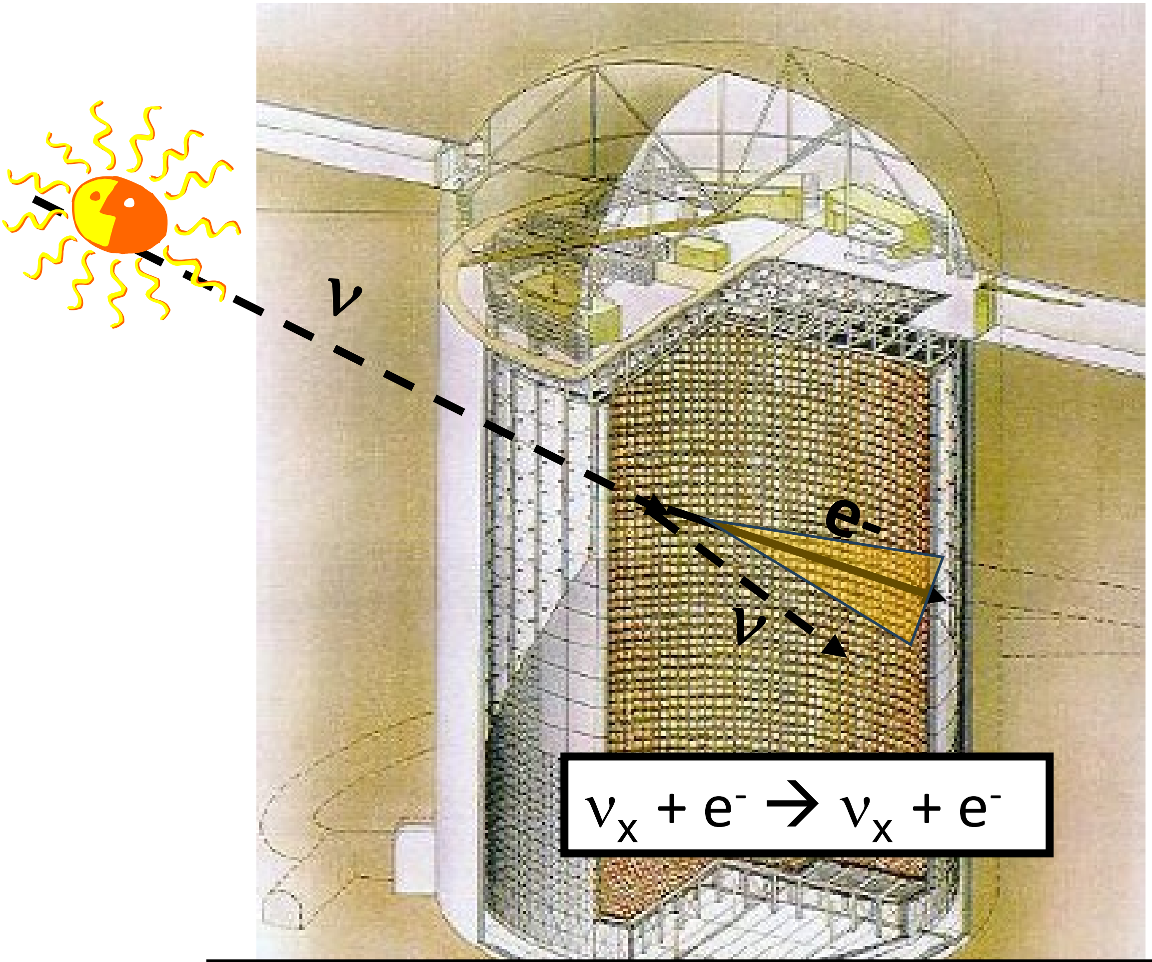
Water Cerenkov detectors have been very important for solar neutrino physics

Example: SuperKamiokande

Core: 50ktons of water contained in a cylindrical tank d~40m, h ~40m

10000 photomultiplier tubes pointing towards the center to view the Cherenkov light;

N.B.: the scattered electron has a direction which is very close to that of the neutrino



$\nu_x + e^- \rightarrow \nu_x + e^-$

@ Kamioka Mine, Hida City, (Japan)

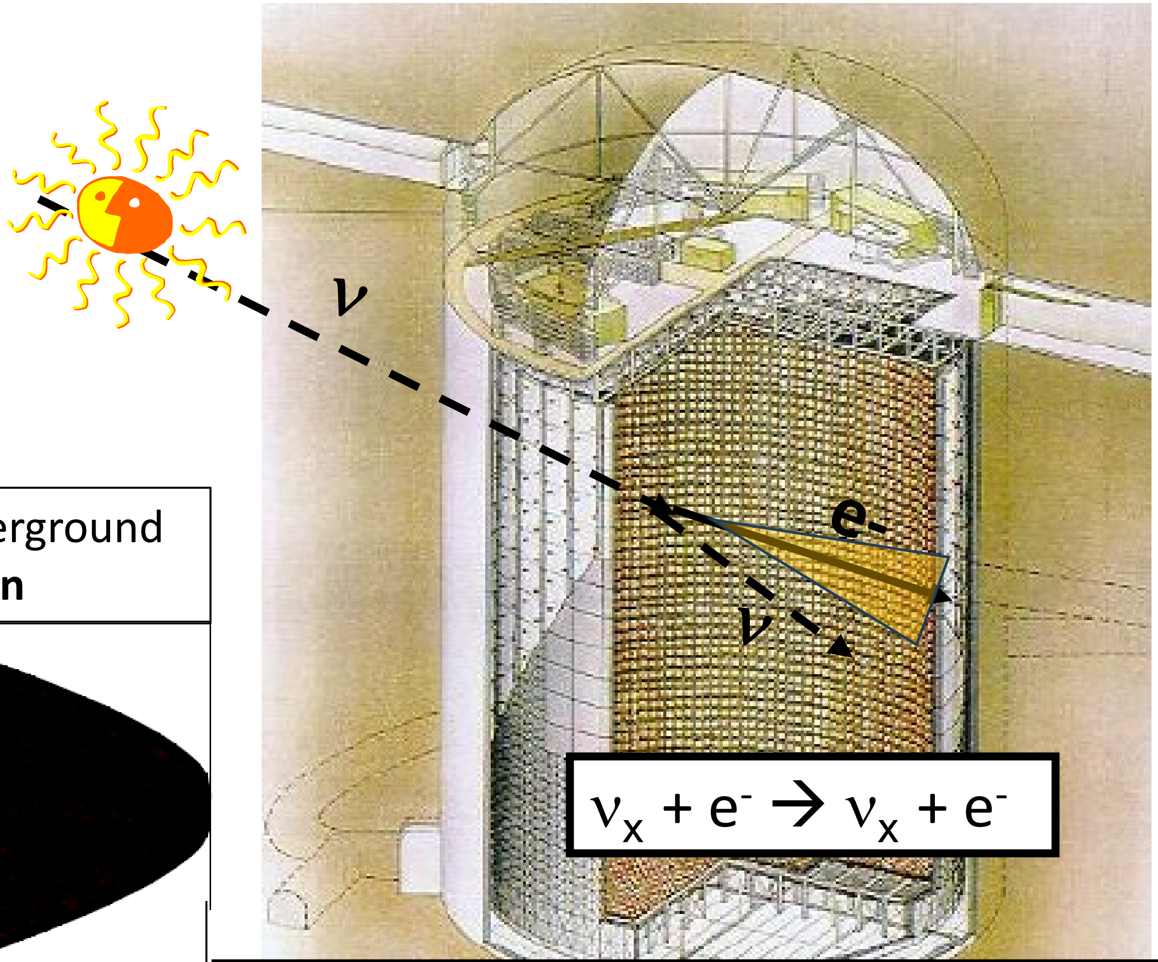
Reconstructing direction in Cerenkov detectors

Water Cerenkov detector have been very important for the solar neutrino physics

Example: SuperKamiokande

For each event

- Number of photons → Energy ($\sigma(E)/E$~20%)
- Cherenkov light is directional → direction of electron ($\sigma(\theta)$: 40^0)



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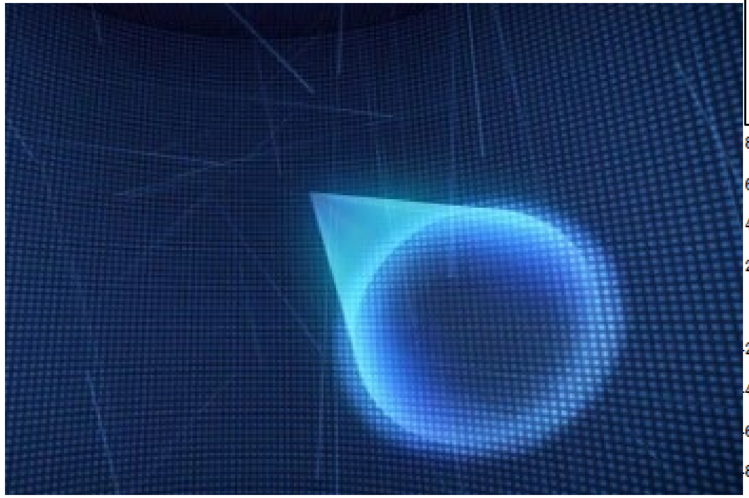
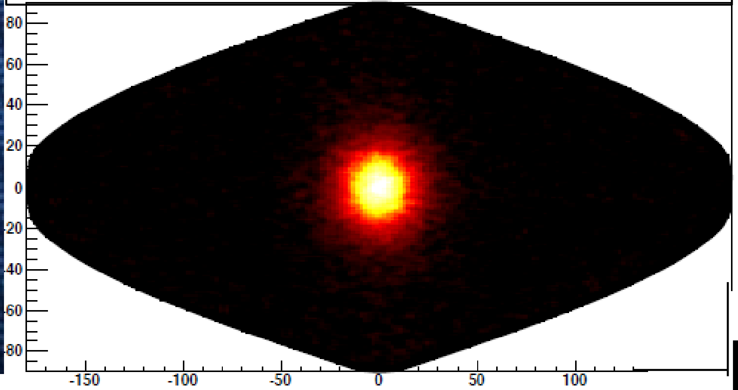


Seeing the Sun from underground

The Eye of Sauron



Reconstructing direction with liquid scintillators

Scintillation light is emitted isotropically → information regarding the particle direction is lost

However, together with the scintillator light, some Cerenkov light is emitted (<1%)

- It is possible to exploit it to obtain some directional information;
- The CID (Correlated and Integrated Directionality) method (Borexino);

CID exploits the same principle used in SuperKamiokande

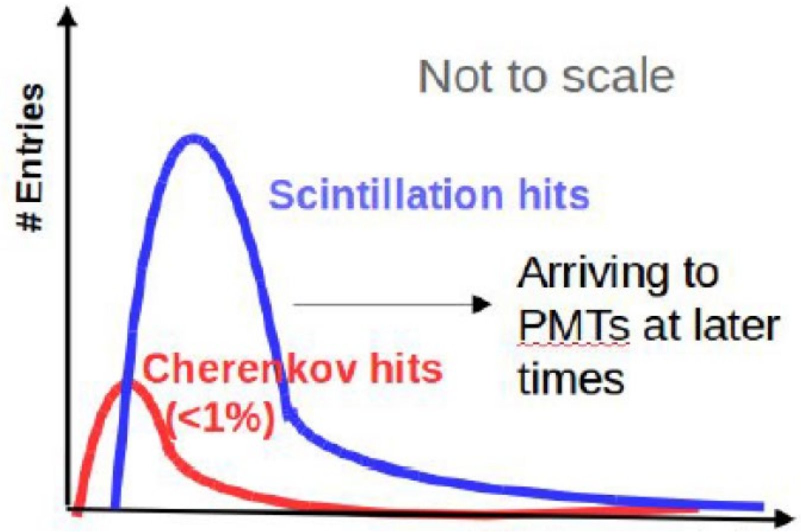
1. When solar neutrinos interact via the $\nu + e \rightarrow \nu + e$ reaction, the electron is mostly scattered forward → its direction is strongly correlated with the Sun position;
2. The Cerenkov light carries info on the electron direction;

There is a complication:

- In SuperKamiokande there were ONLY Cerenkov photons;
- In Borexino, Cerenkov photons are overwhelmed by scintillation photons;

Reconstructing direction with liquid scintillators

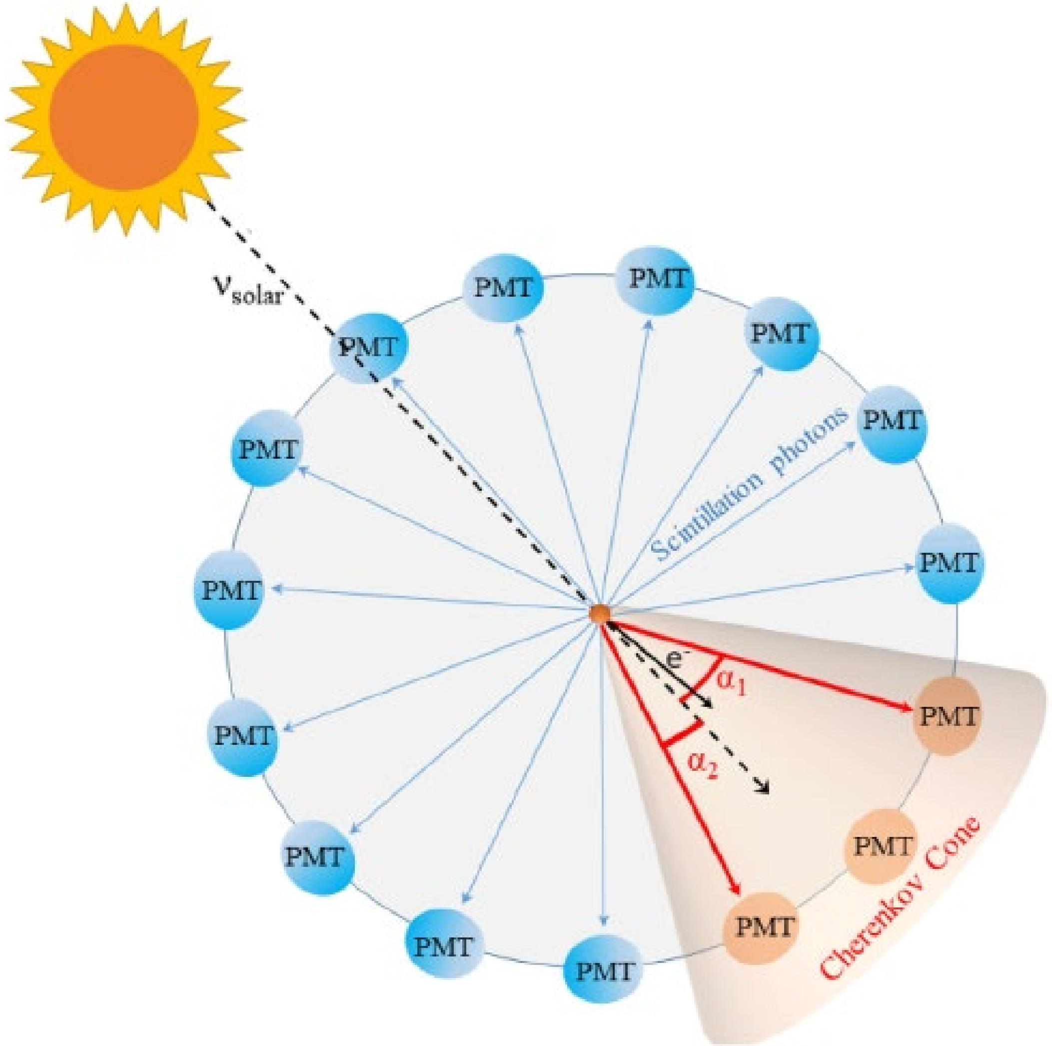
- Cerenkov photons are emitted instantaneously;
- Scintillation photons instead follow the characteristic emission time distribution ($0<\tau_i < 500$ns) → in average they are detected few ns later;

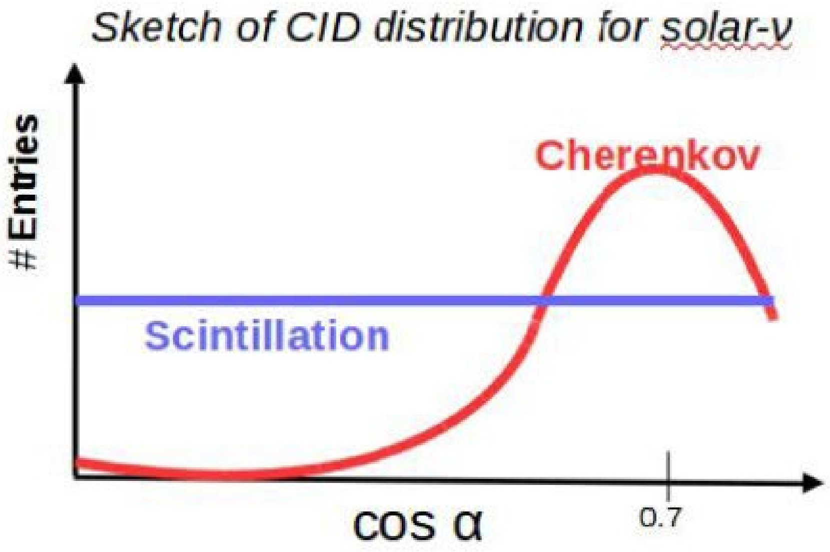


The 1st detected photon has the highest probability to be a Cerenkov photon, followed by the 2nd, 3rd, … with decreasing probability..

Using only the "early" photons, the probability that they are Cerenkov is enhanced

Reconstructing direction with liquid scintillators

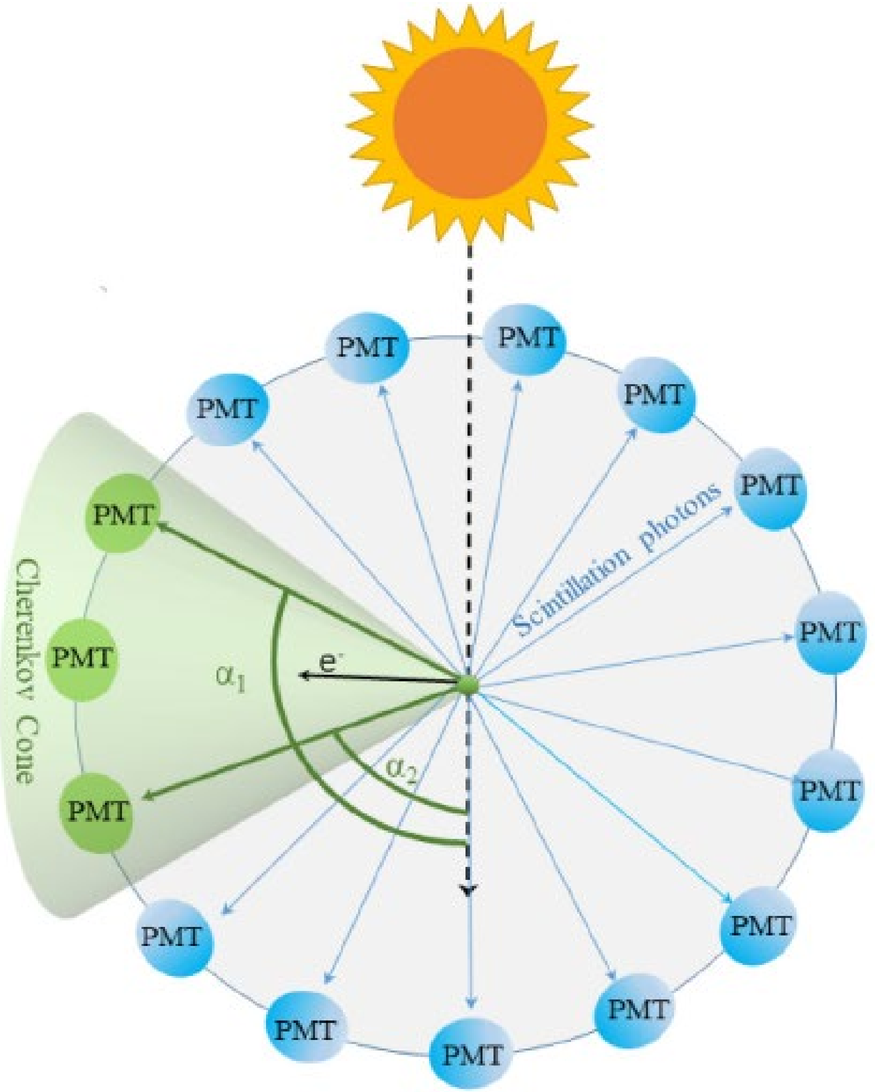


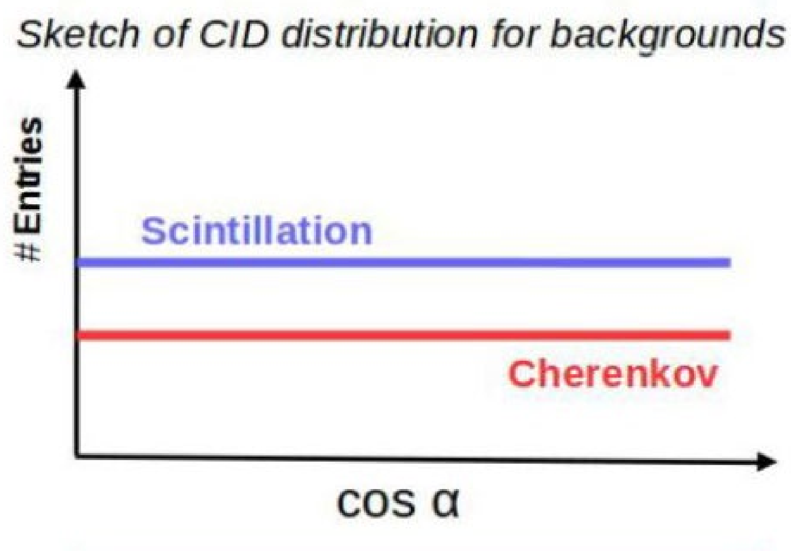


For Cerenkov photons
→ cosα distribution peaks at ~0.7

For scintillation photons
→ cosα distribution is flat

Reconstructing direction with liquid scintillators



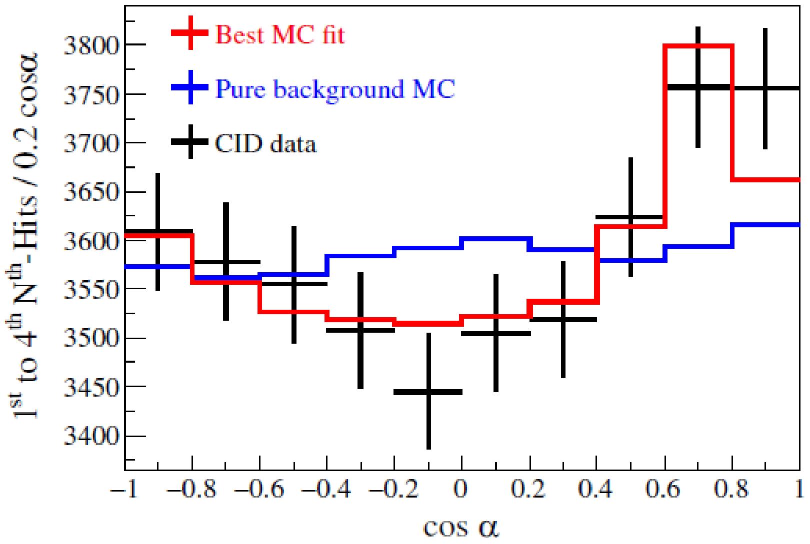


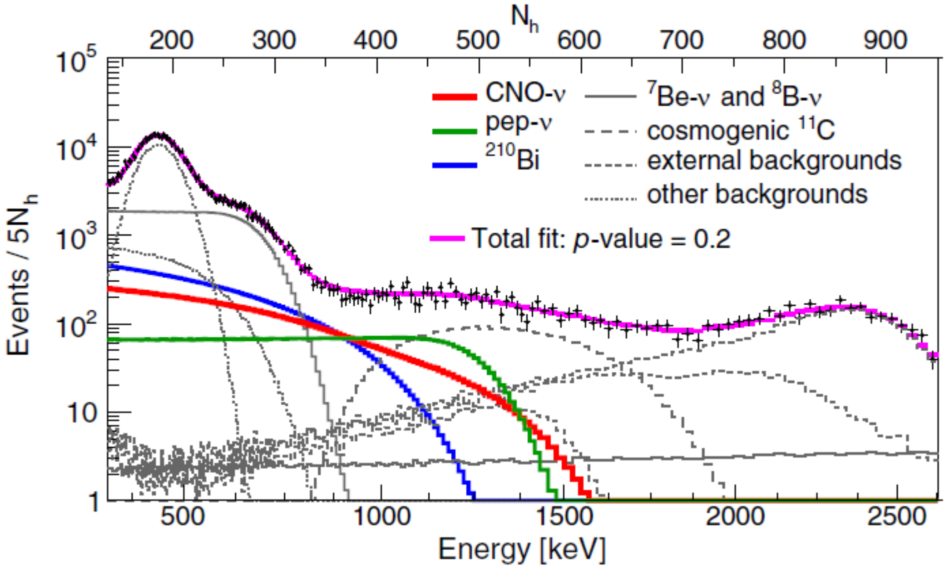
For Cerenkov photons
→ cosα distribution is flat

For scintillation photons
→ cosα distribution is flat

Reconstructing direction

- An histogram of cosα is built for data and it is fitted as the sum of signal and background to extract the total number of solar neutrinos and the total number of background events;





- Combining the CID result with the fit of the energy distribution of events, Borexino has obtained the best measurement of the solar CNO neutrino flux

Phys.Rev.D 108, 102005 (2023)

CNO	$6.7^{+1.2+0.3}_{-0.7-0.4}$	**+30%** **-12%**	$(6.7^{+1.2+0.3}_{-0.8-0.4})x10^8$	**4.88(1±0.11) x10^8 (HZ)** **3.51(1±0.10) x10^8 (LZ)**

Scintillator detectors: the future

The INFN School on Underground Physics

Scintillator detectors: the future

Several ideas are under study for innovative scintillator detectors. I will focus on:

Hybrid scintillators

- Designed to exploit simultaneously the advantages of scintillation and Cherenkov light;
  - Advantage of scintillation light: better energy resolution →possibility to go to low threshold;
  - Advantage of Cherenkov light → directionality;

Opaque scintillators

- A complete change of paradigm! instead of aiming at transparent material, make the scintillator very opaque and equipe it with a web of scintillating fibers to collect the light near to where it is produced

Hybrid Scintillators

Several ideas are under study for innovative scintillator detectors. I will focus on:

Hybrid scintillators

- Designed to exploit simultaneously the advantages of scintillation and Cherenkov light;
  - Advantage of scintillation light: better energy resolution →possibility to go to low threshold;
  - Advantage of Cherenkov light → directionality;

N.B.: Scintillation photons are background for the direction reconstruction! → to reconstruct direction, Cerenkov photons must be separated from scintillation photons

Separation of scintillation and Cerenkov photons

- **Spectral separation**: exploits the fact that scintillator and Cerenkov light have different waveleghts;
- **Time separation**: exploits the fact that scintillator and Cerenkov light have different photon time distributions;

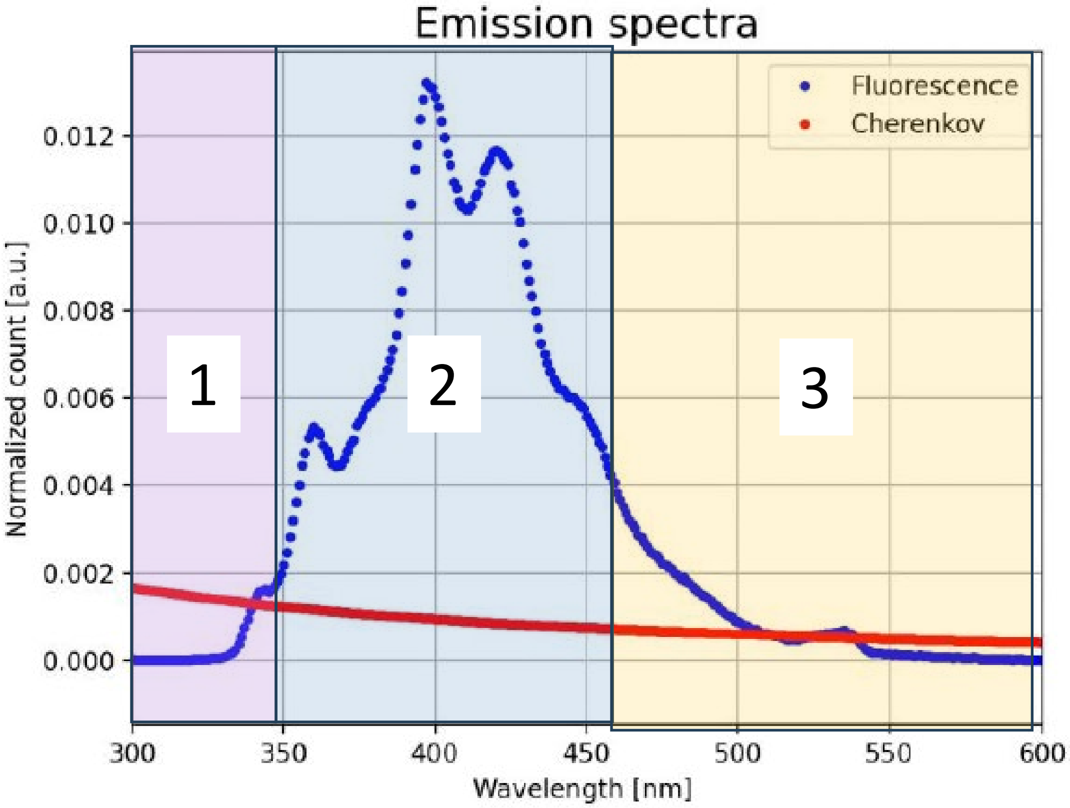
Hybrid Scintillators: spectral separation

- The Cerenkov light has a wide range of wavelengths (follows $1/\lambda^2$ distribution)
- The fluorescence light is peaked in a narrow region centered around ~400 nm

Region 1 (λ <350 nm): dominated by Cerenkov light which is absorbed and re-emitted with the fluor spectrum;

Region 2 (350< λ <450 nm): dominated by fluorescence. Common PMTs have maximum sensitivity in this region;

Region 3 (450< λ< 900 nm): light is dominated by Cerenkov. Red sensitive PMT have maximum sensitivity in this region;



Hybrid Scintillators: spectral separation

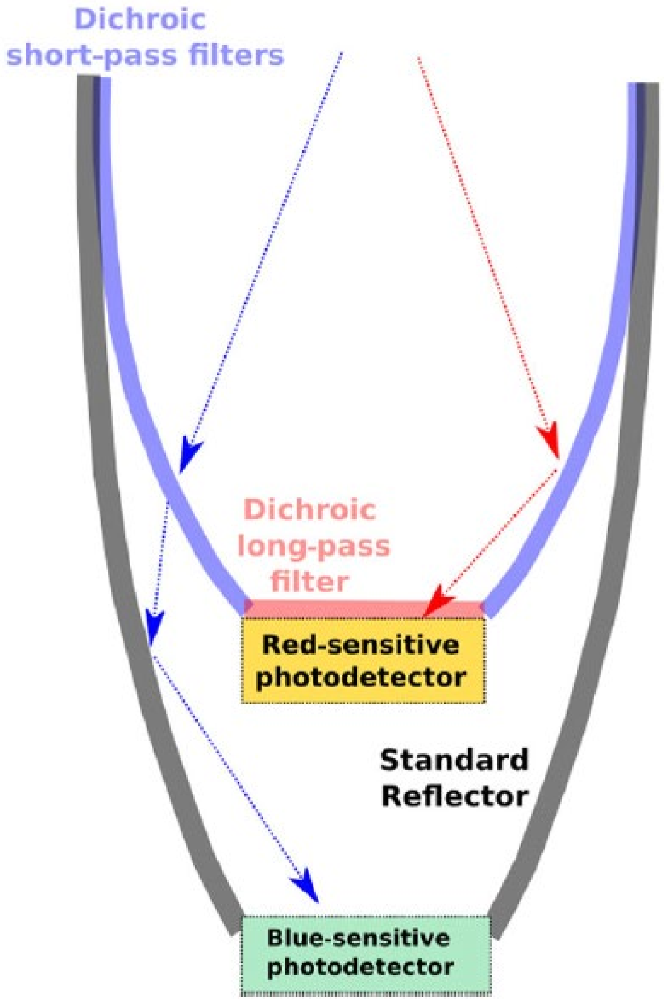
Dichroicon

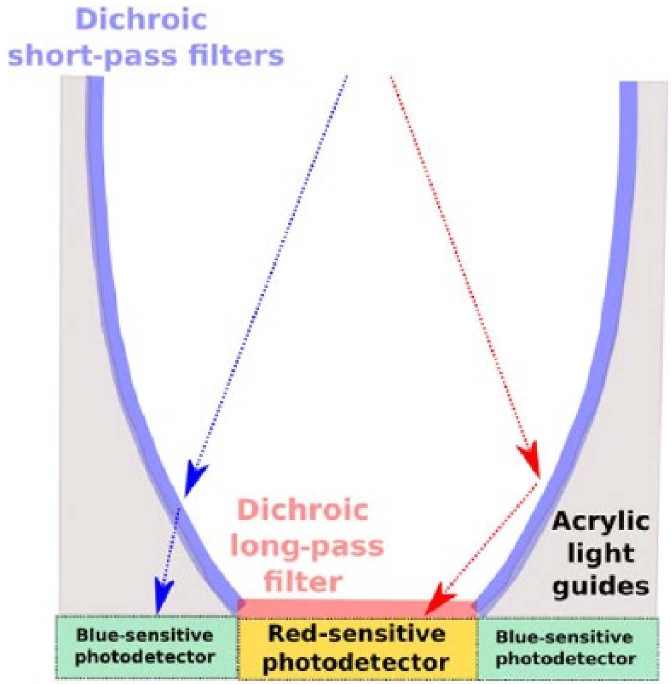
Exploit dichroic filters to:

- direct higher wavelength photons (mostly Cerenkov) to Red-sensitive PMTs;
- lower wavelength photons (mostly scintillation) to standard PMTs

For more details see:

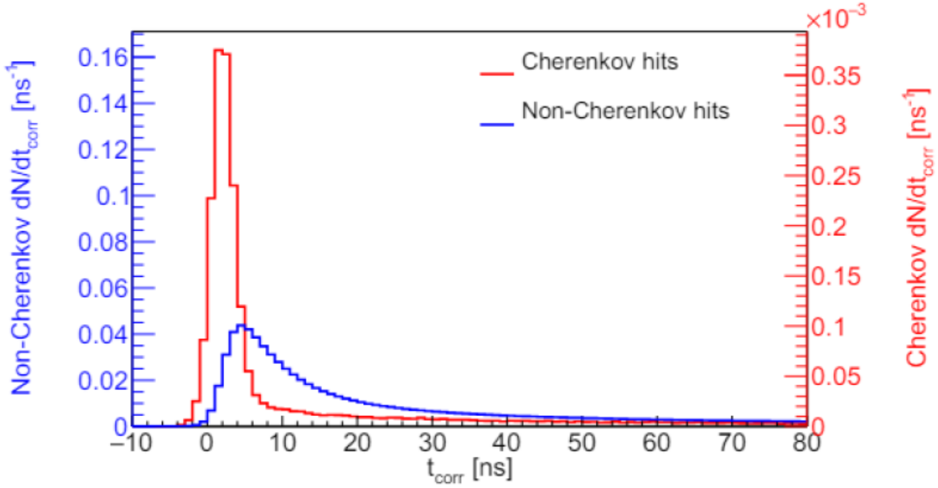
Tanner Kaptanoglu et al. ''Spectral photon sorting for large-scale Cherenkov and scintillator detectors'', Phys.Rev. D 101 (2020) 7.





Hybrid Scintillators: time separation

Time separation
It is based on the same concept as CID: Cerenkov light is emitted instantaneously, while scintillator light is delayed by several ns;



PROBLEM: in standard scintillators, Cerenkov photons are too few (<1%) with respect to scintillation one and cannot be separated on an event-by-event basis;

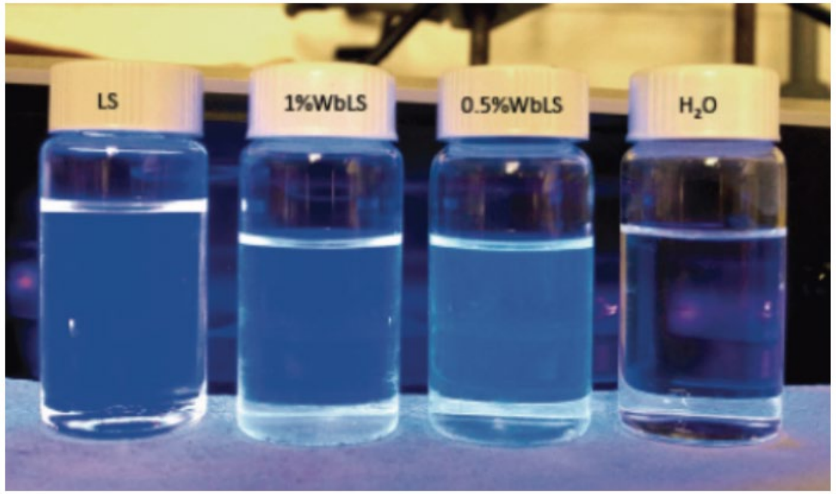
Two possible solutions has been envisioned

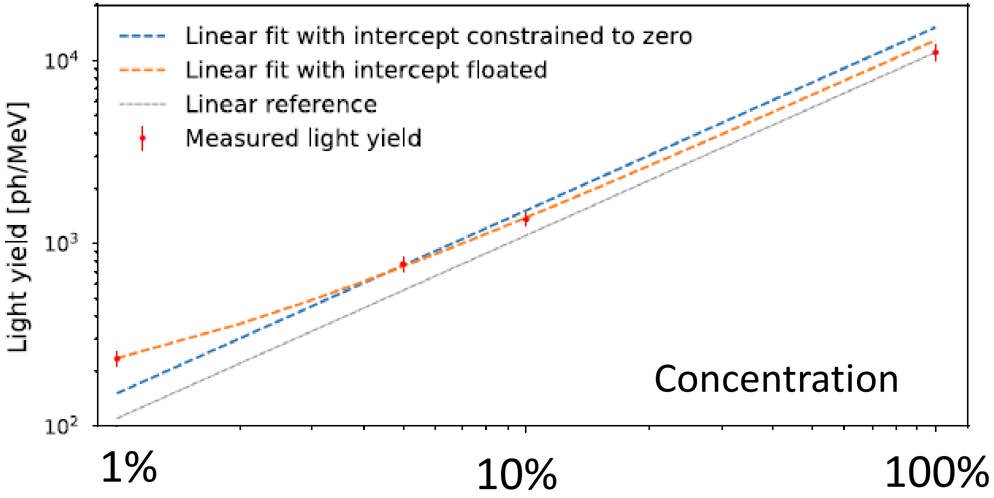
- **Water Based Liquid Scintillators (WbLS):** diluting the liquid scintillator in water, the relative proportion between Cerenkov and scintillation light can be modulated to increase the Cerenkov/scintillation ratio;
- **Slow Liquid Scintillators (SLS):** adding other solvents to the primary one (for example DIN) it is possible to slow down the scintillation emission time to separate it better from Cerenkov

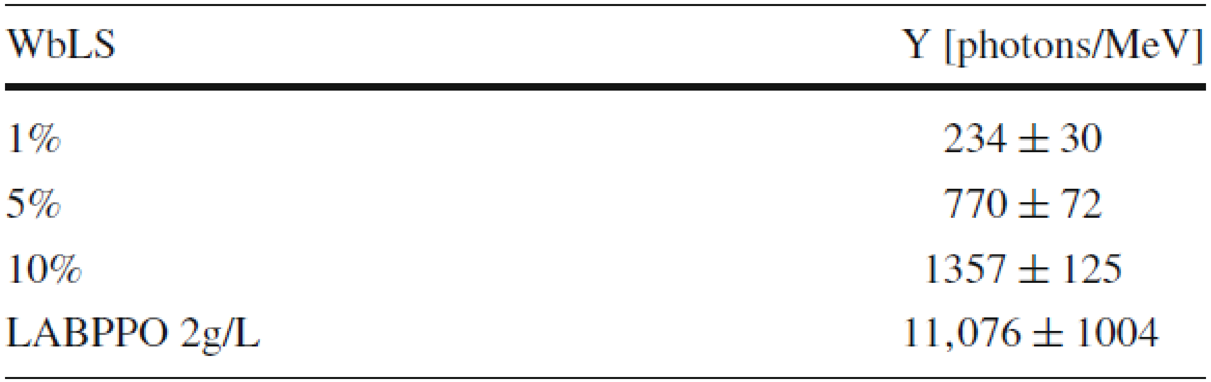
Hybrid Scintillators: time separation

Water Based Liquid Scintillators (WbLS)

- Small amount of scintillator is diluted in water (from 1% to ~10%);
- To mix the scintillator (oil) with water a surfactant is needed ;
- (surfactant= chemical compounds which decreases the surface tension between two liquid. This enables water to mix with oil);
- Light Yield is smaller with respect to Standard Scintillators;
- Light Yield varies ~linearly with the concentration of LS;







WbLS	Y [photons/MeV]
1%	234 ± 30
5%	770 ± 72
10%	1357 ± 125
LABPPO 2g/L	11,076 ± 1004

Eur.Phys.J. C (2020) 80:867

Hybrid Scintillators: time separation

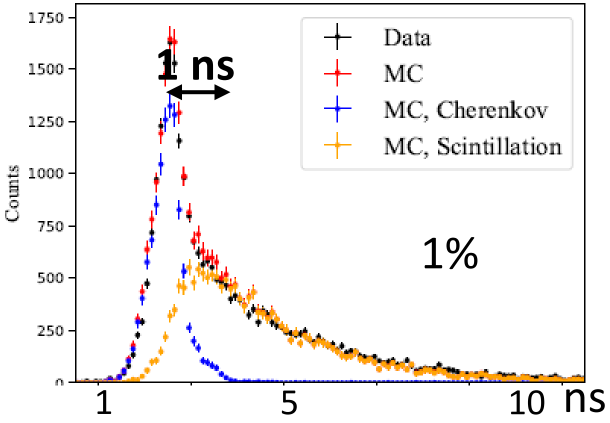
Water Based Liquid Scintillators (WbLS)

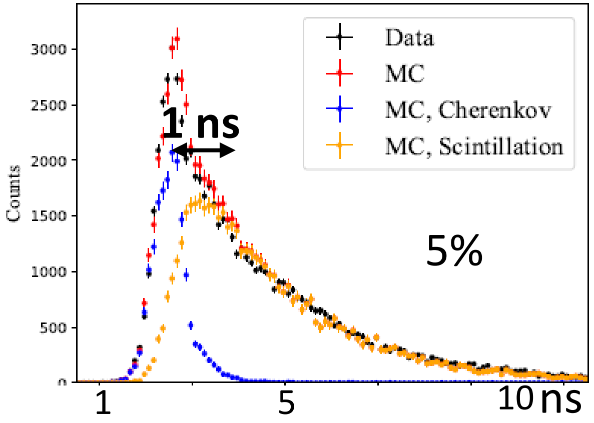
Advantages

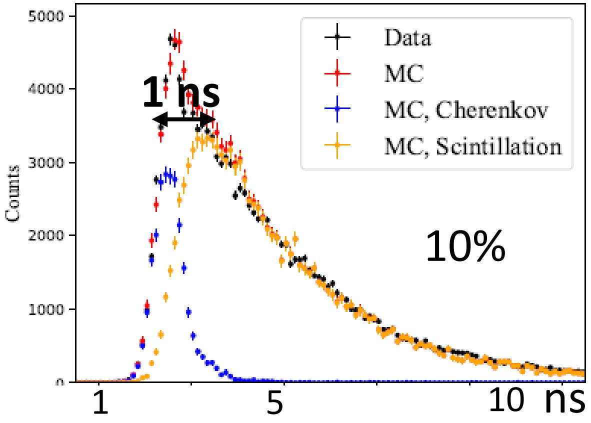
- WbLS are more transparent than standard LS
- WbLS are cheaper than standard LS;
- Metallic ions (Gd for example) can be loaded;
- Directionality is possible;

Disadvantages

- Light Yield is significantly smaller than standard scintillators (1/10, 1/100);
- WbLS may be unstable in time;







Time resolution < 100ps;

N.B.: in order to efficiently separate the Cerenkov from the scintillator signal it may be necessary to use photodetectors with enhanced timing resolution, like LAPPD (Large Area Picosecond Photodetectors);

Hybrid Scintillators: time separation

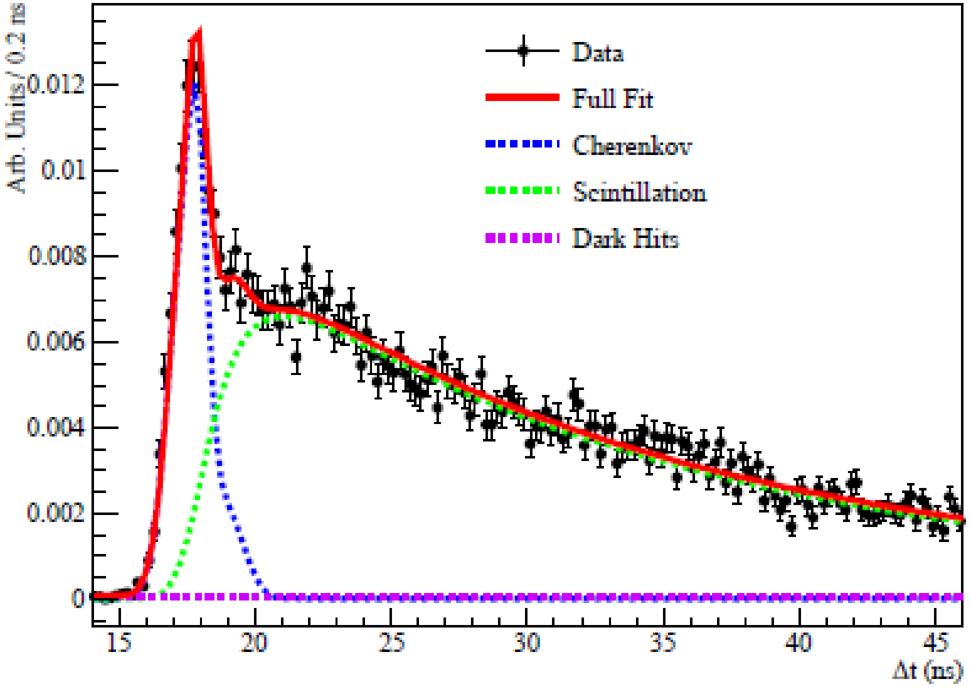
Slow Liquid Scintillators (SLS)

- In order to separate Cerenkov from scintillator light, another possibility is to delay the scintillator light by ~ 10 ns or more;

- The LS can be slowed down by reducing the fluor concentration BUT in this way LY is reduced significantly wrt standard LS;

➢ **Best is to blend the solvent (typically LAB) with DIN which is known to stretch the emission in time;**

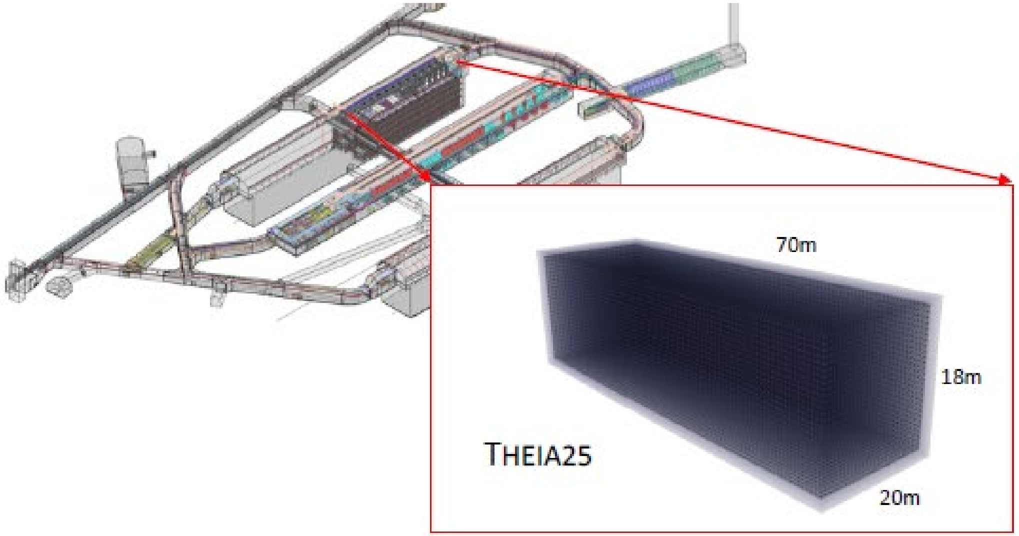
- The LY in these cocktails is similar to the one of Standard Scintillators;
- The mixture has proved to be stable in time;



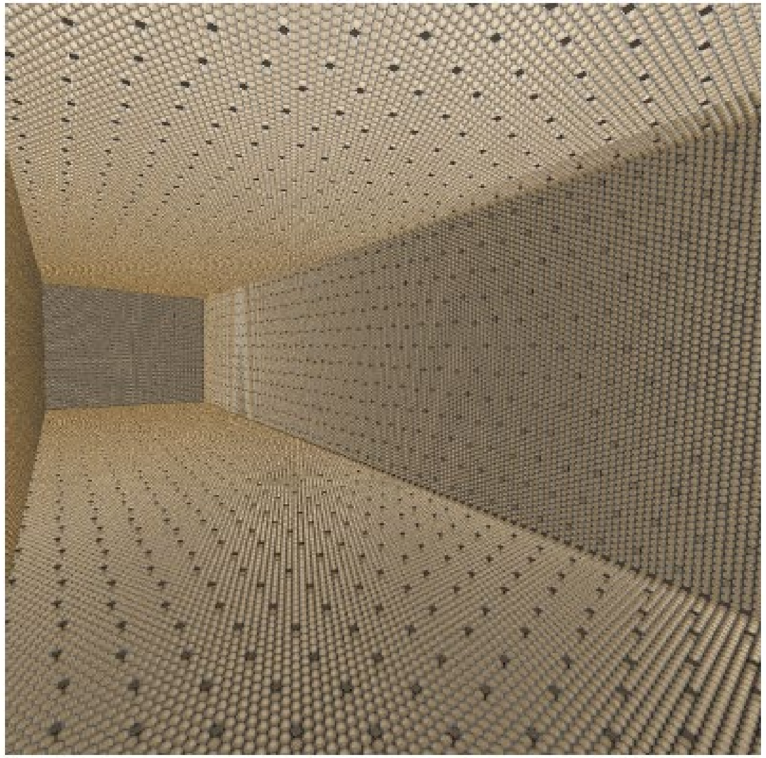
LAB (90%) + DIN (10%) + PPO (1 g/l)

Hybrid Scintillators: THEIA

- Proposed experiment to be located in the same location as DUNE (long baseline neutrino experiment)
- Theia will be located at SURF (Sanford Underground Research Facility)- South Dakota;
- It will contain 25kt of WbLS
- **Multi-purpose detector:** far detector for LBNF beam →study δ_{CP}, NMO ... Solar neutrinos, SN neutrinos..



''THEIA: Summary of physics program'' M.Atkins et al. arXiV:2202.12839

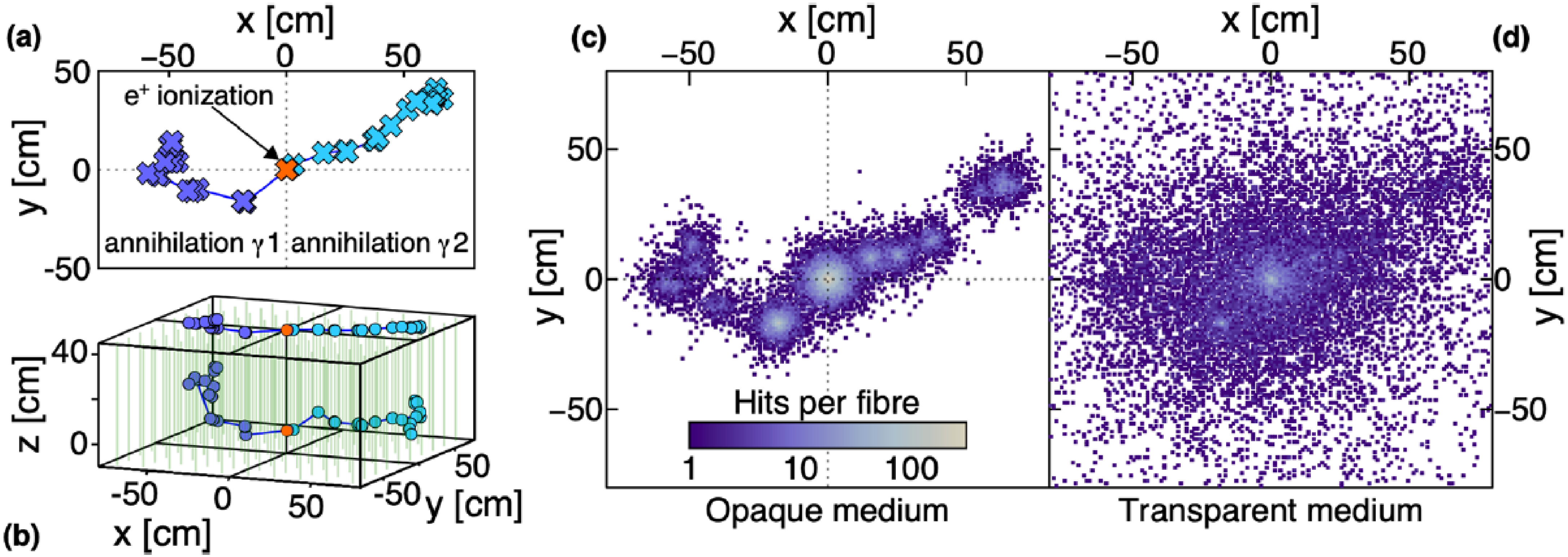


Coverage
Regular PMTs (86%)
LAPPDs (4%)

Opaque Scintillators: LiquidO

THE IDEA: make a scintillator with a very small scattering length (and relatively high absorption length);

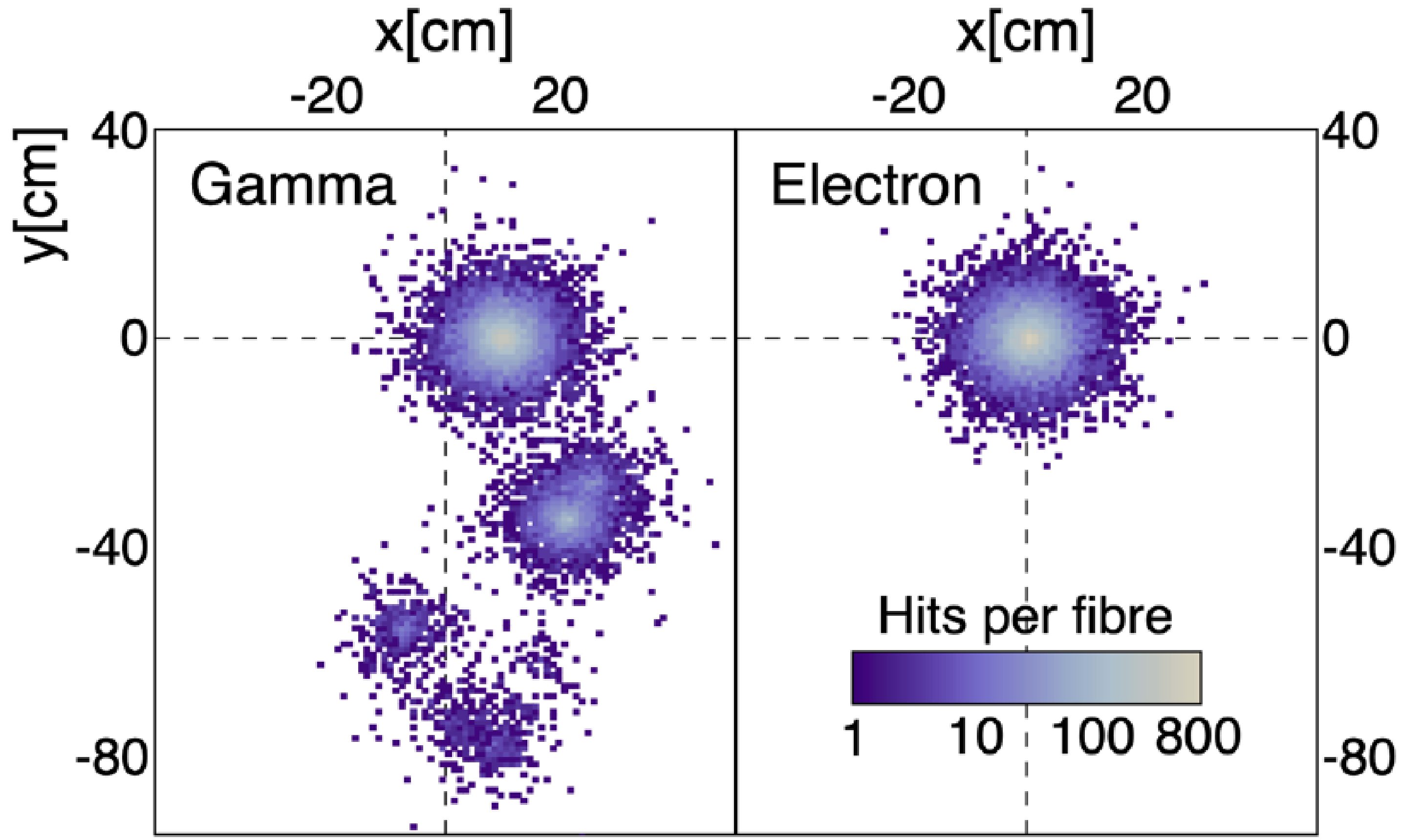
- Equipping the scintillator volume with a lattice of optical fiber, it is possible to collect light very close to where it was produced → tracking is possible!

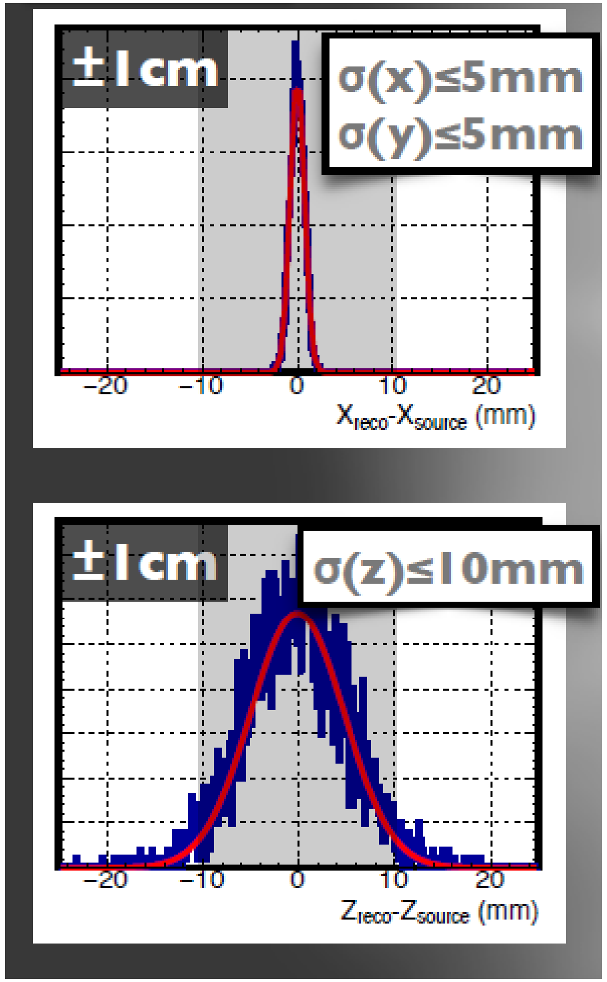


https://doi.org/10.1038/s42005-021-00763-5

Opaque Scintillators: LiquidO

This technique also makes it possible to distinguish electrons from gammas



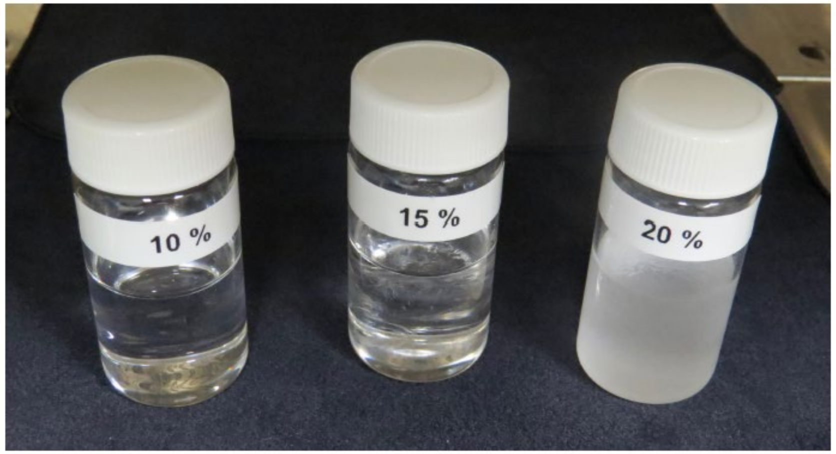


Opaque Scintillators: LiquidO

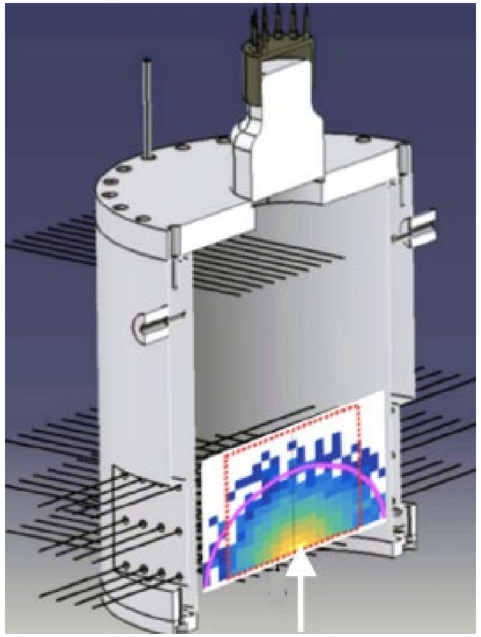
NoWaSH (New Opaque Wax Scintillator)

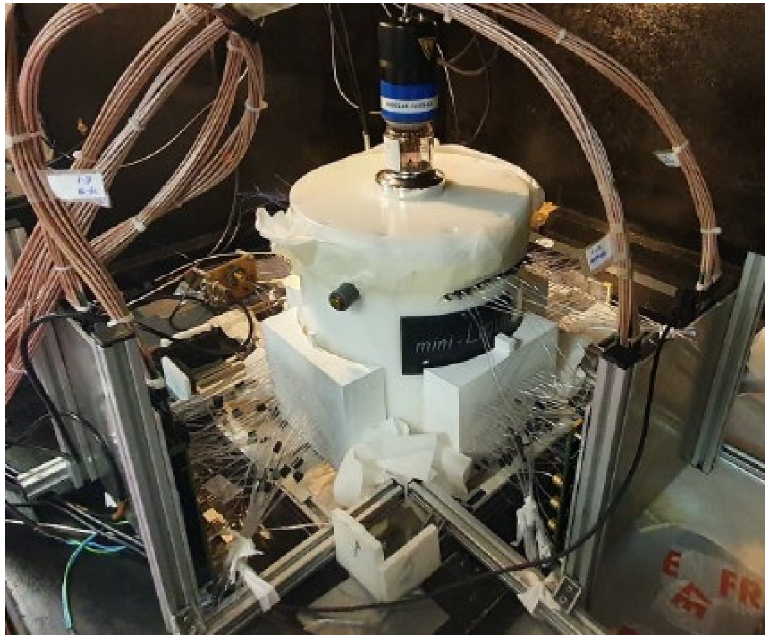
LAB + PPO + Paraffin Wax (10%-20% in weight)

- At high temperature (30^0 - 40^0 degrees) it is transparent
- At lower temperature (~ 25^0)it become opaque;



Novel Opaque Scintillator for Neutrino Detection
C. Buck et al. JINST 14 P11007 (2019)





Mini-LiquidO

- 10 liters of NoWASH;
- 56 fibers in 2 orthogonal planes;

Warning: A critical point is the stability in time and uniformity of these materials

Conclusions

- Organic Liquid Scintillator detectors have played and still play a crucial role in rare events search, in particular neutrino physics;

The important features which have made the scintillator technique so successful are:

- Scalability to large masses;
- Very low levels of radioactivity;
- Relatively good energy resolution;
- Pulse shape discrimination possibility;
- Fast time response;

- The lack of directionality in scintillators can be overcome in the future by materials where Cerenkov light is combined with scintillator light (WbLS or SLS)
- R&D studies are ongoing for a change in the scintillator paradigm: opaque scintillator may be used to finely track particles, even at low energies;